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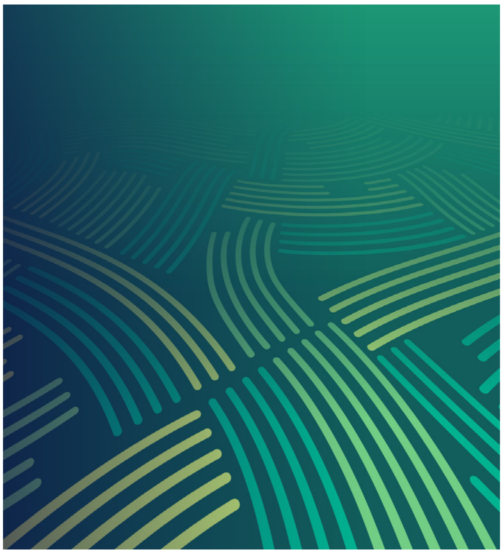
Anticipate, Innovate, Transform

Cultivating Resilience: Climate Change & Sustainable Agriculture

CONTENT



CULTIVATING RESILIENCE: CLIMATE CHANGE & SUSTAINABLE AGRICULTURE

BY ATHULA GINIGE, GUEST EDITOR

Climate change is upon us — and is affecting global food production, forcing us to devise various adaptation strategies. The Food and Agriculture Organization of the United Nations (FAO) estimates that climate change could push 122 million more people, mainly farmers, into extreme poverty by 2030 and increase cereal prices by 29% by 2050, among other adverse effects.[1] Rising temperatures, changing precipitation patterns, extreme weather events, and alterations in pest and disease dynamics pose formidable challenges to global agricultural systems.

Although agricultural activities significantly contribute to the emission of greenhouse gases (GHGs), agriculture also holds immense potential for mitigating climate change and adapting to its effects. FAO reports that a third of global soils are degraded, releasing 78 gigatons of carbon dioxide into the atmosphere and costing more than 10% of GDP through lost biodiversity and ecosystem services. Around 14% of food, worth US $400 billion, is lost between harvest and when it reaches retailers. According to FAO estimates, total food losses and waste cause 8% of GHG emissions.[2] Thus, climate-smart agricultural practices and better-coordinated agriculture value chain activities aimed at minimizing losses can contribute to mitigating climate change. Developing new crop varieties and cultivation methods that could adapt to climate change is also essential.

This issue of *Amplify* explores the complex relationship between climate change and agriculture, highlighting the urgent need for innovative solutions to ensure food security and sustainable farming practices. We take readers on a journey from the frontlines of climate change's impact on smallholder farmers to the potential of AI and data-driven technologies to transform the entire pathway across the agri-food supply chain. The issue collectively emphasizes several key themes: the impact of climate change on agriculture, the need for sustainable and climate-resilient practices, the role of technology (especially AI), the value of traditional knowledge, and the importance of collaboration and stakeholder engagement. In particular, the authors recognize agriculture's vulnerability to changing weather patterns, rising temperatures, extreme weather events, water scarcity, soil degradation, and pest/disease dynamics.

Without a doubt, there is a crucial need for sustainable agricultural practices that enhance resilience to climate change impacts. It has become vital to optimize resource use and reduce environmental impacts to ensure long-term food security.

As explored in this issue, AI, in particular, can help tackle climate change challenges and promote sustainable agriculture. AI technologies in precision farming, crop monitoring, automated irrigation, robotics, and market forecasting can optimize resource use, improve yields, and support data-driven decision making.

Yet, traditional agricultural knowledge must play a major role in adapting to climate change and enhancing resilience. The authors advocate for integrating traditional practices with modern technologies to develop context-specific solutions that are both effective and culturally sensitive.

Finally, our experts emphasize the need for collaboration among diverse stakeholders — farmers, technology providers, researchers, policymakers, and consumers — to address the challenges. They advocate for collective action, knowledge sharing, and supportive policies to facilitate innovation in pursuit of food security.

> **FARMERS ARE WITNESSING FIRSTHAND THE EFFECTS OF CLIMATE CHANGE — FROM SHIFTING MONSOON PATTERNS & INCREASED HEAT WAVES TO WATER SCARCITY & SOIL DEGRADATION**

IN THIS ISSUE

The issue begins by grounding us in the lived experiences of farmers grappling with the increasingly unpredictable realities of a changing climate. My colleagues, Santosh Kumari and Sanju, and I shed light on the challenges faced by farmers in Haryana, India, a region heavily reliant on agriculture. Farmers are witnessing firsthand the effects of climate change — from shifting monsoon patterns and increased heat waves to water scarcity and soil degradation. The article emphasizes that these farmers are not passive victims; they are actively adapting by modifying planting schedules, experimenting with climate-resilient crops, and drawing on generations of traditional knowledge. However, we make it clear that existing adaptation strategies may not be enough to address the scale of the challenge. Some even augment the factors leading to climate change, underscoring the need for systemic solutions.

Having established the urgency of the situation, the next article focuses on technology's role in empowering farmers to navigate these challenges. Philip Webster, Habib Hussein, Kajetan Widomski, Jonathan Jeyaratnam, Ruth Bastow, and Mark Matthews of Arthur D. Little introduce AI as a powerful tool capable of assisting farmers in making informed decisions about adopting new technologies and practices. The authors acknowledge the complexity of farming systems and the difficulty in identifying appropriate solutions amid a rapidly evolving technological landscape. They propose a use case–driven approach, using AI tools to analyze a range of factors, such as market trends, climate data, regulatory environments, and farm-specific variables, to recommend the most suitable innovations. Two case studies (strawberry farmers in the UK grappling with water regulations and oasis farmers in Morocco facing increasing aridity) demonstrate how this approach can be tailored to address local challenges and opportunities.

The potential of AI is clear, but our next article cautions against viewing technology as a silver bullet. Successfully integrating AI into agriculture requires a nuanced understanding of the social, cultural, and ecological contexts in which it is deployed. Vijaya Lakshmi and Jacqueline Corbett explore this concept, arguing that a conjoint-learning approach (one that combines the precision of AI with the rich tapestry of traditional agricultural knowledge) holds the key to unlocking truly sustainable solutions. Their article presents three case studies from India, each showcasing how farmers are blending generations-old practices with AI-powered tools to enhance decision-making, optimize resource use, and adapt to changing conditions. For example, an organic orchard in western India is combining AI-based disease detection with traditional fertilization methods, and a crop farm in the north is integrating AI weather predictions with local knowledge to more effectively manage water resources. The authors highlight the successes and the challenges of this approach, underscoring the need for ongoing dialogue and collaboration between farmers, technology developers, and policymakers to ensure that AI solutions are contextually relevant and culturally sensitive.

CLIMATE CHANGE POSES A SIGNIFICANT THREAT TO GLOBAL FOOD SECURITY

Building on these insights, Cutter Expert San Murugesan provides a comprehensive overview of how AI is transforming agriculture on a global scale. His piece delves into a wide range of AI applications, from precision agriculture and automated irrigation to crop monitoring, robotics, and market forecasting. It showcases the potential of AI to not only increase yields and optimize resource use but to reduce waste, minimize environmental impact, and enhance farmers' livelihoods. Murugesan emphasizes the need for a multi-stakeholder approach, calling for increased investment in R&D, the creation of supportive policies, and targeted efforts to address the barriers to AI adoption, including high implementation costs, data privacy concerns, and the digital divide.

The issue concludes by broadening the lens beyond individual farms to consider the entire agri-food supply chain (ASC). Climate change poses a significant threat to global food security, as extreme weather events disrupt ASCs, affecting food production, logistics, and consumption. Kasuni Vidanagamachchi, Dilupa Nakandala, and I examine the vulnerabilities of ASCs, drawing on lessons learned from adaptations made during the pandemic. We posit that long-term viability, rather than short-term resilience, is essential for these systems to withstand prolonged crises. The article highlights the importance of diversifying food supply methods, incorporating local production, community-based sharing, and digital technologies to enhance adaptability and responsiveness to disruptions. Through a case study from Sri Lanka, we demonstrate how a combination of government support, community engagement, and digital innovation enabled effective adaptation during the pandemic. We advocate for a comprehensive, collaborative approach that integrates advanced technologies with sustainable practices to build more resilient and viable ASCs capable of ensuring food security amid the uncertainties of climate change.

This issue of *Amplify* highlights the need for a multifaceted approach that embraces both the power of technology and the wisdom of tradition to address the complex challenges facing agriculture in the 21st century. By fostering collaboration and innovation across the food system, we can strive to create a more resilient, sustainable, and equitable future for agriculture. In closing, the issue's overarching conclusions include:

- **Climate-resilient agriculture demands a multifaceted approach.** There is no single solution to the challenges facing agriculture in a changing climate. Effective response requires a combination of technological advancements, sustainable farming practices, policy interventions, and a deep understanding of local contexts.
- **AI can be a powerful ally in the fight against climate change.** AI has the potential to revolutionize agriculture by optimizing resource use, improving yields, and enhancing resilience. However, rather than acting as a standalone solution, AI should be seen as a tool to augment and enhance existing knowledge and practices.
- **Traditional knowledge is an invaluable asset.** Traditional agricultural knowledge, honed over generations of experience, holds critical insights into local ecosystems, climate adaptations, and sustainable practices. Integrating this knowledge with modern technologies is essential for developing contextually relevant and culturally sensitive solutions.
- **The entire agri-food supply chain must adapt.** Building a climate-resilient food system requires going beyond individual farms to consider the interconnectedness of production, processing, distribution, and consumption. This involves addressing challenges related to infrastructure, logistics, market access, consumer behavior, and waste reduction across the supply chain.

- **Collaboration is essential for success.** There must be collaboration among all stakeholders involved in the food system, from farmers and technologists to policymakers and consumers. Achieving food security and sustainability in a changing climate requires breaking down silos, fostering dialogue, and working together to develop and implement innovative solutions.

These themes suggest that the future of agriculture depends on a paradigm shift that embraces both technological innovation and traditional wisdom. By fostering collaboration, promoting sustainable agriculture, and leveraging the power of AI in a responsible and contextually sensitive manner, we can create a more resilient, equitable, and food-secure world.

REFERENCES

1 "FAO's Work on Climate Change: United Nations Climate Change Conference 2019." Food and Agriculture Organization of the United Nations (FAO), 2019.

2 FAO (see 1).

About the guest editor

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CLIMATE CHANGE ADAPTATION:

PERCEPTIONS & ACTIONS OF SMALLHOLDER FARMERS

Authors

Santosh Kumari, Athula Ginige, and Sanju

The adverse impacts of climate change affect both developed and developing countries, but developing countries and poor smallholder farmers are more vulnerable as they sorely lack adequate adaptive capacity. Smallholder farmers' high dependence on rain-fed agriculture makes them especially susceptible to the profound impacts of climate change. This is compounded by elevated levels of poverty, inadequate infrastructure, and lagging technological development. Consequently, climate change is set to adversely affect many agricultural-dependent communities in developing countries, aggravating food insecurity and global poverty.[1]

The adverse impacts of climate change on agriculture include rainfall, temperature, heat waves, weed modifications, pests and microbes, global changes in atmospheric carbon dioxide, ozone levels, and sea level fluctuations.[2] Climate change has destructive effects on plant growth and crop production. Weather variations collectively have positive and negative outcomes, but the negative effects are more pronounced. Extreme weather disasters, such as drought and flooding, have an outsized impact on vulnerable populations.[3]

The agriculture sector has the potential to contribute to climate change mitigation and increasing resilience through adaptation.[4] Farmers' adaptive capacity involves their ability to apply new strategies and solutions to address the adverse effects of global warming on food production.[5] The ability to adapt is especially vital for smallholder farmers in developing countries.

Adaptation requires planning, investment, and formulation of relevant policies to enhance farmers' resilience to climate change. Our recent study focused on how climate change is causing severe problems for farmers in Haryana, India. In this article, we review farmers' perceptions of climate change and provide sample adaptation measures being adopted to enhance resilience. Such insights are vital to guide policy formulation.

RESPONSE TO CLIMATE CHANGE BY HARYANA FARMERS

Since agriculture is affected by climate change in several ways, farmers can provide first-hand observations of climate change impacts and adaptation options. Our study looked at the impact of climate change in two of Haryana's agroclimatic zones: southwestern and northeastern.

ADAPTATION REQUIRES PLANNING, INVESTMENT & FORMULATION OF RELEVANT POLICIES TO ENHANCE FARMERS' RESILIENCE TO CLIMATE CHANGE

Haryana is frequently referred to as "India's food mine." Approximately 80% of the state's population is directly or indirectly engaged in agriculture. In addition to producing enough grain for its own needs, Haryana contributes significantly to the nation's grain supply, including a vast amount of basmati rice. The state produces a large amount of winter crops, including rice, wheat, bajra (pearl millet), and maize. Its autumn crops include sugarcane, groundnuts, maize, and paddy. The state's northwestern region is ideal for growing rice, wheat, vegetables, and temperate fruits, while the southwest is best suited for producing premium agricultural products (e.g., tropical fruits, exotic vegetables, and herbal and medicinal plants).

FARMERS' AWARENESS OF CLIMATE CHANGE

Our study involved 240 farmers in the Fatehabad and Hisar districts. Figure 1 shows that Haryana farmers are well aware of climate change effects and illustrates a precise ranking. Most farmers in the study said they are seeing more frequent heat waves and greater fluctuation in the onset of monsoons. A decrease in average rainfall, an increase in average temperature and dry spells, an increase in maximum and minimum temperatures, and an uneven distribution of rainfall also ranked high in awareness. The lowest area of awareness is around prolonged cold weather.

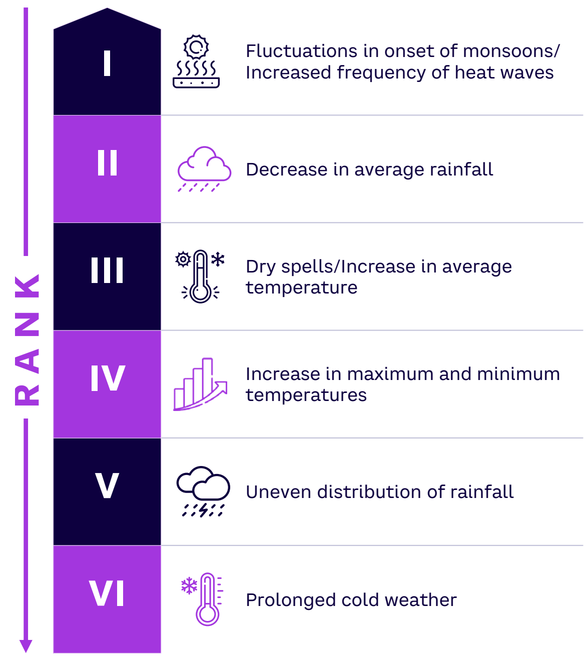

Figure 1. Farmer awareness of climate change indicators

The study data suggests that the current climate pattern is characterized by increasing temperature extremes, variability in precipitation, and significant impacts from fluctuations in monsoon onset and heat waves.

Nearly 90% of respondents reported they face huge losses because of water accumulation after heavy rainfalls. More than half (58%) cited drought, storm, weeds, crop disease, and pest outbreaks as current common causes of agricultural losses. Seventy-three percent said erratic rainfall had caused major losses in agricultural productivity in the last five years. The majority (93%) said environmental pollution (from pesticides, chemical fertilizers, and waste materials) is a common cause of agricultural loss. Fifty-five percent suggested that climate change has adversely affected soil fertility, crop rotation, and water shortages.

CLIMATE CHANGE EFFECTS & ADAPTATIONS

Over the past few decades, Haryana has seen a significant shift toward growing paddy, sugarcane, and wheat, driven by unpredictable climatic conditions, market demand, government policies, and the relatively high profitability of these crops.[6]

As stated, most farmers attribute crop failure to water accumulation following heavy rainfall and extreme weather events like heat waves. Erratic rainfall disrupts planting and harvesting schedules, affecting crop yields. Extreme weather conditions, such as droughts, floods, and heat waves, pose significant risks to crop health and farmer productivity. Temperature fluctuations, particularly high temperatures and heat waves during critical growth periods, can lead to crop stress and failure.[7] These climatic events greatly disturb the critical natural conditions required for crop cultivation (see Figure 2).

MICRO-LEVEL CHANGES & MACRO-LEVEL CHALLENGES

The changing climate has led to a rise in macro-level challenges. Soil degradation and water scarcity are two such issues, primarily caused by wind, water erosion, and grazing. Water erosion is caused by heavy rainfall that causes runoff, carrying away soil particles and depleting soil nutrients, leading to reduced soil fertility. Additionally, overextraction of groundwater

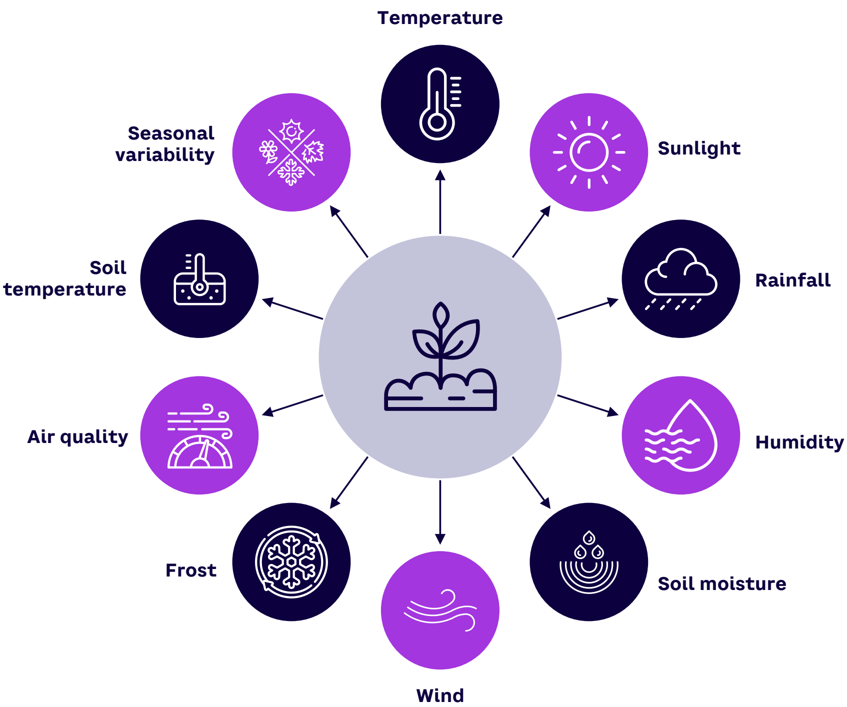

Figure 2. Factors that affect crop cultivation and yield

has become a critical issue, with more than half of groundwater withdrawals exceeding recharge each year. This leads to the continuous depletion of groundwater resources. Paddy cultivation, which is highly water-intensive, exacerbates this problem by lowering water tables. Traditional irrigation methods, such as flood irrigation, further contribute to water scarcity by wasting a significant amount of water.[8]

Table 1 shows how various climatic events affect temperature, soil, water, and crops. An increase in temperature leads to higher evaporation and nutrient depletion in soil, along with increased water demand and heat stress in crops, resulting in reduced yields and faster maturation.

Conversely, a decrease in temperature slows soil warming, reduces water demand, and can delay crop germination, with a risk of frost damage. Excessive rainfall can cool temperatures but often results in waterlogged soil, erosion, and increased runoff, causing root rot and fungal diseases.

Droughts raise daytime temperatures, dry out soil, and reduce water availability, leading to wilting, stunted growth, and lower yields. High humidity slightly cools the air but can cause waterlogging and increases the risk of fungal and bacterial diseases. Low humidity accelerates soil drying and water loss, raising irrigation needs and risk of drought stress. Strong winds may cool the air but they erode soil and increase evaporation, leading to physical crop damage. Frost can reduce water availability and cause significant crop damage, delaying growth and perhaps crop loss.

CASE STUDY: COTTON CROP CULTIVATION IN HARYANA

Haryana farmers, particularly those involved in cotton cultivation, are increasingly affected by climate change. The region has experienced a significant rise in temperature, leading to an increase in pest attacks on cotton crops, reducing yields and threatening the viability of this traditional crop. The rise in temperature has exacerbated water scarcity, further diminishing yields by delaying plant flowering.

Faced with these challenges, many farmers have reconsidered their crop choices and are choosing paddy cultivation. Paddy is perceived as more resilient to the changing climate and is supported by government price guarantees. (The government promises to buy any harvest that farmers cannot sell as much or more than the market price.)

CLIMATIC EVENT	EFFECT ON TEMPERATURE	EFFECT ON SOIL	EFFECT ON WATER	EFFECT ON CROPS
Increase in temperature	Rise in average temperature	Increased soil evaporation, possible nutrient depletion	Higher water demand, reduced water availability	Heat stress, reduced yields, faster crop maturation
Decrease in temperature	Drop in average temperature	Slower soil warming, risk of frost heaving	Reduced water demand, slower evaporation	Delayed germination, risk of frost damage
Excessive rainfall	Possible cooling effect	Waterlogged soil, erosion, nutrient leaching	Increased runoff, potential flooding	Root rot, fungal diseases, crop lodging
Drought	Increase in daytime temperature	Soil drying & hardening, loss of organic matter	Reduced water availability, higher salinity	Wilting, stunted growth, reduced crop yields
High humidity	Minor cooling effect	Reduced soil evaporation, risk of waterlogging	Slower water evaporation	Increased risk of fungal & bacterial diseases
Low humidity	Minor warming effect	Faster soil drying, potential crusting	Increased water loss, higher irrigation needs	Enhanced evaporation, risk of drought stress
Strong winds	Possible cooling effect	Soil erosion, loss of topsoil	Increased evaporation from soil & plants	Physical crop damage, desiccation
Frost	Sharp drop in temperature	Soil freezing, potential heaving	Reduced soil water availability due to freezing	Frost damage, delayed growth, potential crop loss

Table 1. Impact of climatic events on temperature, soil, water, and crop health

This provides a guaranteed income, making it an attractive option for farmers looking to optimize their revenue in uncertain times.

However, the shift to paddy cultivation has brought its own set of problems. One of the most significant issues is the practice of residue burning, which has severe environmental consequences, including soil fertility degradation. Residue burning after harvesting is common, due to the time and money involved with removing the residue from the previous crop before the start of the next season. Crop-residue burning leads to a decline in soil fertility, directly impacting future crop yields. Over time, this soil-health reduction threatens farmers' long-term earning potential, trapping them in a cycle of reduced productivity and income.

This scenario highlights the complex challenges that Haryana farmers face due to climate change. The shift to paddy cultivation offers a temporary solution to the immediate impacts of climate change but introduces new problems that could undermine the long-term sustainability of agriculture in the region. Addressing these issues requires a comprehensive approach that considers not only immediate economic benefits, but also the long-term environmental and social implications of farming practices in a changing climate.

MITIGATION EFFORTS & ADAPTIVE STRATEGIES

Farming methods that support soil health are essential for making agriculture more sustainable while improving food-growing conditions. In northwest India, efforts to eliminate the practice of burning crop residue have shown promise. This practice destroys soil nutrients, contributes to air pollution, and emits greenhouse gases that exacerbate global warming.[9]

Smallholder farmers, who often lack the knowledge and resources to cope with climate change, are beginning to use adaptive strategies like altering planting dates and developing climate-resilient crops. Unpredictable and erratic rainfall can trigger drought conditions, leading to crop failures. Conservation agriculture, which involves principles like minimal soil disturbance, crop rotation, and permanent soil cover, has been identified as a pathway to sustainable agriculture. In particular, zero tillage, which leads to higher yields with less variability in crops like wheat, is being promoted. No-till practices have been highlighted as an alternative to conventional tillage, which is crucial for mitigating the impact of climate change through carbon sequestration.[10-13]

Despite these efforts, there are serious barriers to effective climate change mitigation in India. Resource constraints, such as high production costs, high interest rates, volatile market prices, and rising costs of fossil fuel-based inputs, have trapped many farmers in a vicious cycle of debt. Farmers also face challenges related to water shortages, including a lack of hydrological information, a large gap between water demand and supply, water pollution, and the overexploitation of groundwater. Moreover, many farmers lack the technical knowledge to adopt emerging technologies that could help them mitigate the effects of climate change. Economic challenges like low income levels, lack of access to credit, and market volatility further exacerbate the situation, pushing many farmers into debt and financial instability. Inefficient institutions, complex land ownership, and tenure systems also hinder progress.[14-17]

CONCLUSION & RECOMMENDATIONS

This article has highlighted the significant risk posed by climate change to agriculture. In the developing country of India, farmers are aware of these risks and are implementing adaptation strategies. Unfortunately, the long-term effect of some of the adaptation strategies can worsen the situation.

We also explored how micro-level climate events over time can create macro-level challenges that significantly affect agriculture productivity. Without concerted efforts, food security and the incomes of millions of smallholder farmers will be at risk.

Government support for crop insurance and sustainable farming practices can help buffer smallholder farmers from the effects of climate change. Support for drought-resistant crops and improvements in irrigation infrastructure could help farmers manage risks associated with increasingly erratic weather patterns.

Table 2 shows four areas that should be part of any climate adaptation and mitigation framework. Farmer involvement in developing and implementing climate change adaptation strategies is crucial to enhancing agricultural productivity and ensuring the sector's sustainability,[18] and new policies are necessary to control the pollution emitted by agricultural activities.[19]

Much more is needed to help farmers develop and implement effective adaptation and mitigation strategies, and this will require public funding. Humanity's greatest challenge is feeding the world's human population in a sustainable, nutritious, equitable, and ethical way during a period of increasing climate change. Urgent transformation is vital to allow farmers to earn a living while increasing climate resilience and reducing emissions.

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REFERENCES

[1] Adimassu, Zenebe, and Aad Kessler. "Factors Affecting Farmers' Coping and Adaptation Strategies to Perceived Trends of Declining Rainfall and Crop Productivity in the Central Rift Valley of Ethiopia." *Environmental Systems Research*, March 2016.

[2] Raza, Ali, et al. "Impact of Climate Change on Crops Adaptation and Strategies to Tackle Its Outcome: A Review." *Plants (Basel)*, Vol. 8, No. 2, February 2019.

[3] Bryant, Christopher R., et al. "Adaptation in Canadian Agriculture to Climatic Variability and Change." *Climatic Change*, Vol. 45, July 2014.

OBJECTIVE	ACTIONS	EXPECTED OUTCOME
Knowledge dissemination	Strengthen agricultural extension services; organize training workshops; launch awareness campaigns	Improved knowledge & skills among farmers about climate change
Resource accessibility	Provide subsidies for inputs; invest in efficient irrigation systems; offer microfinance opportunities	Increased access to affordable inputs & resources
Supportive policies	Implement incentives for sustainable farming; strengthen market linkages; increase public funding for research	Enhanced support for sustainable agricultural practices
Climate resilience	Promote climate-resistant crops; support adaptive strategies; develop efficient irrigation systems	Improved resilience to climate impacts on farms

Table 2. Initial roadmap for mitigating climate change impacts

[4] Gikunda, Raphael, David Lawver, and Juma Magogo. "Culture as a Predictor of Effective Adoption of Climate-Smart Agriculture in Mbeere North, Kenya." *Advancements in Agricultural Development*, Vol. 3, No. 2, May 2022.

[5] Mabe, Franklin Nantui, Daniel Bruce Sarpong, and Yaw Osei-Asare. "Adaptive Capacities of Farmers to Climate Change Adaptation Strategies and Their Effects on Rice Production in the Northern Region of Ghana." *Russian Journal of Agricultural and Socio-Economic Sciences*, Vol. 11, No. 11, October 2012.

[6] Kumar, Surender. "Assessment of Impacts of Climate Change on Trend and Pattern of Wheat Crop in Haryana: A Geographic Analysis." *International Journal of Basic and Applied Research*, Vol. 8, No. 2, February 2018.

[7] Wakweya, Rusha Begna. "Challenges and Prospects of Adopting Climate-Smart Agricultural Practices and Technologies: Implications for Food Security." *Journal of Agriculture and Food Research*, Vol. 14, December 2023.

[8] Deen, Sahab, and Sanju Bala. "Changing Cropping Pattern in Haryana: A Spatio-Temporal Analysis of Major Food Crops." *International Journal of All Research Education and Scientific Methods (IJARESM)*, Vol. 9, No. 3, March 2021.

[9] Thakur, J.K., et al. "Crop Residue Burning: Consequences on Soil Microbes." *Harit Dhara*, Vol. 2, No. 2, July–December 2019.

[10] Altieri, Miguel A., and Clara I. Nicholls. "The Adaptation and Mitigation Potential of Traditional Agriculture in a Changing Climate." *Climatic Change*, Vol. 140, September 2013.

[11] Baul, Tarit Kumar, and Morag McDonald. "Integration of Indigenous Knowledge in Addressing Climate Change." *Indian Journal of Traditional Knowledge (IJTK)*, Vol. 14, 2015.

[12] Powlson, David S., et al. "Limited Potential of No-Till Agriculture for Climate Change Mitigation." *Nature Climate Change*, Vol. 4, July 2014.

[13] Kumari, Mamta, and Jagdeep Singh. "Water Conservation: Strategies and Solutions." *International Journal of Advanced Research and Review*, Vol. 1, No. 4, 2016.

[14] Sarma, G.V. Prasada. "Campaign to Reduce Use of Chemical Fertilizers, Pesticides." *The Hindu*, 28 May 2016.

[15] Yadav, Reeta Devi, and Rita Goel. "Problems of Cotton Farmers in Haryana." *International Journal of Current Microbiology and Applied Sciences*, Vol. 8, No. 3, 2019.

[16] Hussain, Siraj, and Kriti Khurana. "Minimum Price Support, Maximum Gain for Farmers." *Deccan Herald*, 9 March 2024.

[17] Chintapalli, Prashant, and Christopher S. Tang. "The Impact of Crop Minimum Support Prices on Crop Production and Farmer Welfare." *UCLA Anderson Review*, March 2021.

[18] "Sustainable Agriculture Practices in the State." National Bank for Agriculture and Rural Development (NABARD), accessed July 2024.

[19] Sharma, Sonali. "India's Climate Change Policy: Challenges and Recommendations." Indian School of Public Policy, 16 January 2023.

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AI CAN HELP FARMERS MEET THE INNOVATION ADOPTION CHALLENGE

Authors

Philip Webster, Habib Hussein, Kajetan Widomski, Jonathan Jeyaratnam, Ruth Bastow, and Mark Matthews

New and effective farming practices are central to sustainably meeting the world's future food needs. But environmental issues, combined with shifting consumer demands, make farming an uncertain, complex, and economically challenging endeavor and one that is highly individual to each farmer.[1-3]

This article summarizes joint thinking by Arthur D. Little (ADL) and the recently established UK Agri-Tech Centre on how best to address these challenges. It reflects our collaborative work on the potential of AI tools to help farmers and other stakeholders identify the best technologies to adopt.

Water quality and scarcity represent some of the biggest challenges affecting food production and food security. Agriculture accounts for about 70% of global water withdrawals, and demand is increasing due to rising temperatures, population growth, demand from other industries, and chronic resource mismanagement.[4] The World Bank estimates that 25%-30% of all freshwater is wasted, costing the global economy US $14 billion annually.[5]

United Nations (UN) data indicates that to meet the world's future food needs, food production will need to increase 70% by 2050.[6] Irrigated land contributes 40% of global food production, yet some countries are already hitting the limits of their renewable water capacity.[7] The Nile, the Colorado, the Ganges, and the Yellow Rivers are all at maximum capacity to support human and environmental demands.[8]

Farming is also a leading source of water pollution. The inappropriate use of fertilizers and pesticides is contaminating rivers and oceans, impacting public health and biodiversity.[9]

At the same time, consumers increasingly expect food to be not only sustainably and responsibly produced, but also inexpensive, not least through pressure from food processors and retailers.

Awareness of these issues has increased in recent years, and legislation and regulatory changes were introduced, but meeting these expectations through more efficient use of water and agricultural inputs is not free and can greatly reduce farmers' profitability.[10]

INNOVATION ADOPTION CHALLENGE

Change is needed (see Figure 1). Advancements in agricultural technologies (agri-tech) will be key to addressing the challenges faced by farmers and our world. Not surprisingly, agri-tech has been booming over the past decade, attracting significant investment from venture capitalists and outpacing investments in many other sectors.

Farmers, commodities suppliers, investors, and governments are well aware of the need for innovation to support more sustainable practices and protect scarce resources. However, due to the complexity and individuality of farming systems, knowing what tech to invest in and under what circumstances (not to mention how to realize benefits) is a significant challenge.

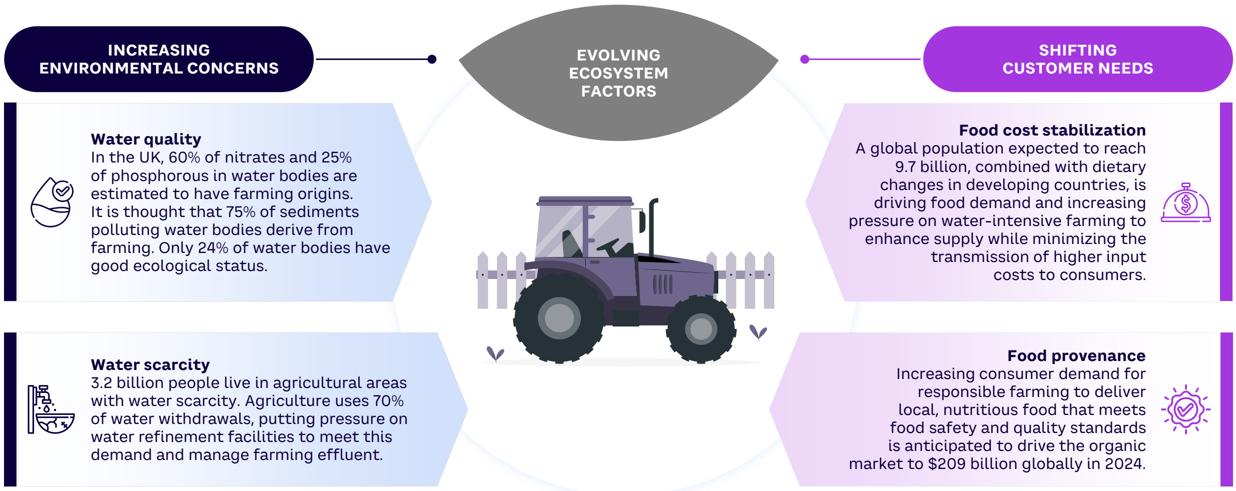

Figure 1. Factors driving the innovation agenda in farming (source: Arthur D. Little)

Each farm has unique geographies, landscapes, climates, soils, crops, and land-use histories. There are multiple factors at play when considering how to maximize crop quality and yields and the many factors that will affect them going forward.[11] When you add variables like climate change, regulations, geopolitics, financing, and rapid rates of technology innovation, decision makers find themselves facing an overwhelming amount of information that limits their ability to make optimal decisions for themselves, society, and the planet in terms of where to innovate and what to adopt.

This decision paralysis limits innovation investments, particularly in areas where technologies are rapidly evolving. ("Should I commit now to a solution that may become obsolete or delay the adoption decision in the expectation of future solutions being better value for my money?")

Recent rapid advances in AI are producing tools that can help, starting with decisions about where to innovate and what to adopt. These tools can also provide information on the broader direction of relevant emerging technologies, informing adopt-now versus adopt-later decisions. Figure 2 shows how AI tools can support innovation decisions.

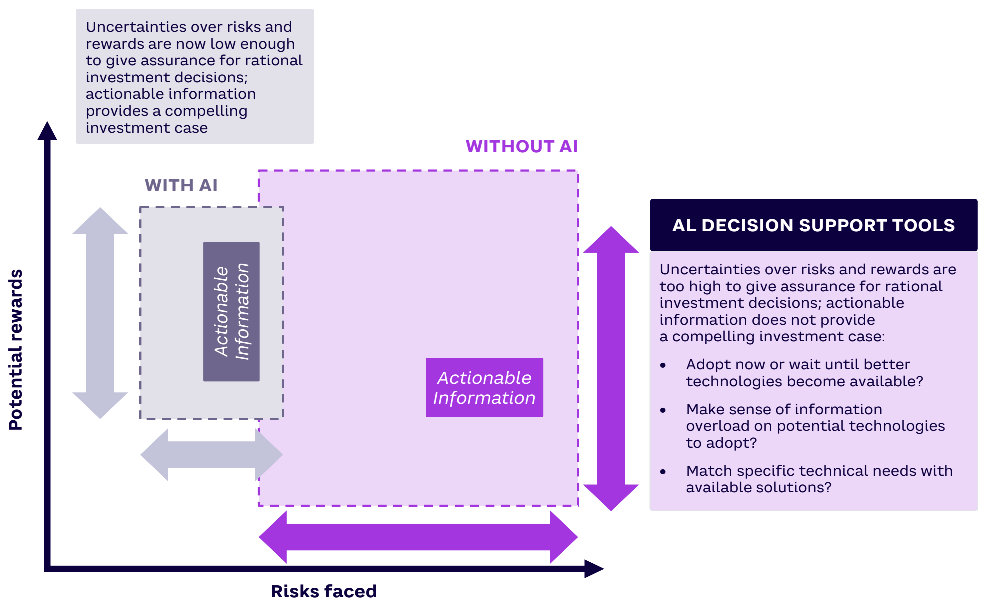

Figure 2. How AI can facilitate agri-tech innovation adoption (source: Arthur D. Little, UK Agri-Tech Centre)

USE-CASE DRIVEN TECHNOLOGY ADOPTION

AI tools can undertake two key tasks for farmers and other food chain stakeholders: (1) understanding the trends, drivers, and uncertainties impacting innovation adoption and (2) identifying technologies related to specific use cases.

To do this, stakeholder needs are identified with an initial prompt (written input) to an AI tool, outlining desired benefits such as increased profits (see Figure 3). This can be followed by using AI tools and/or talking to expert growers to identify key ecosystem and adoption factors.

Ecosystem factors include elements that shape the broader context in which adoption occurs. Adoption factors refer to the specific attributes and conditions that affect the decision-making process of individuals or organizations about whether to adopt a new technology or innovation based on the use case. Both can either facilitate or hinder the integration of new technologies or practices. Examples of factors in each category are provided in Figure 4.

Expertise in creating a strong AI prompt is essential to accurately guide the tool to produce relevant data for subsequent integration with specific use cases and identify optimal technological solutions.

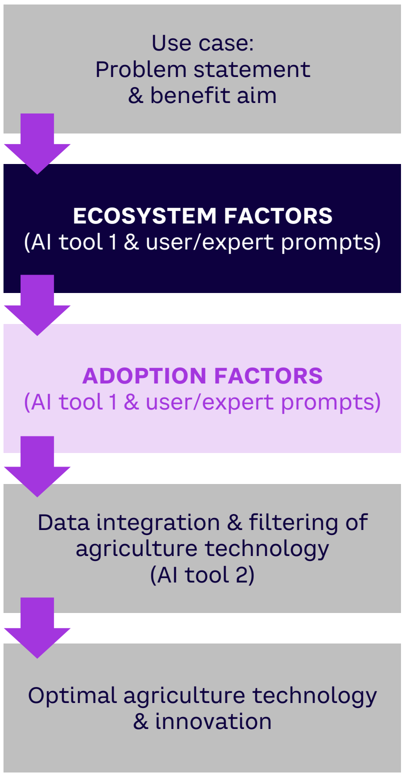

Figure 3. Process for identifying optimal technology choices using AI (source: Arthur D. Little)

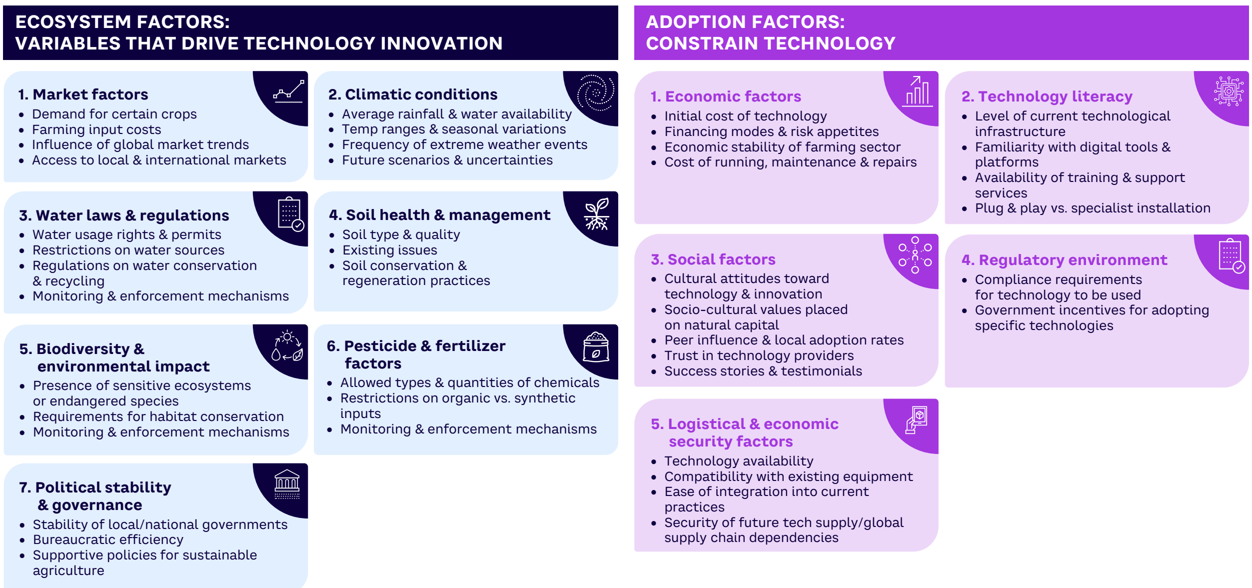

Figure 4. Examples of key variables to be considered during technology identification (source: Arthur D. Little)

To demonstrate the utility of this approach, we present two case studies, one involving strawberry farmers in the UK and the other looking at considerations for oasis farmers in the Draa Valley in Morocco.

CASE STUDY 1: STRAWBERRY FARMERS

UK strawberry growers pursuing greater profits need to identify solutions that enhance their business. A key area for enhancement is water management, in terms of access, use, and disposal. Strawberries have exacting moisture requirements that necessitate intense water use, usually delivered via irrigation.

ECOSYSTEM FACTORS

Identification of suitable agri-tech is impacted by a wide range of ecosystem factors, including market factors, climate conditions, pesticide and fertilizer regulation, and water regulation.

Market factors, including current and anticipated demand and ongoing input costs such as water and labor, influence innovation identification. Strawberry demand is strong, with the market expected to grow at a compound annual growth rate of 5.74% from 2023 to 2028.[12] Despite this, wholesale pricing remained flat between 2021 and 2022 while production costs rose 25% between 2020 and 2022.[13] Ideally, agri-tech solutions will help farmers achieve desired crop yield while minimizing water use and labor costs.

Climate conditions are increasingly volatile and must be considered in any solution searches. Unpredictable periods of drought in the UK threaten water security, a critical consideration given the requirement for consistent and even crop moisture, equivalent to 2.5 L/m2 of water per week throughout the growing season. Identified solutions should aim to maximize water continuity, minimize use, and enhance security.

Pesticide and fertilizer regulations are managed by the UK Chemicals Regulation Division (CRD) of the Health and Safety Executive (HSE), which authorizes pesticide use and places limits on the maximum concentration that can remain in and on consumer crops. The pressure on growers to ensure that produce meets current regulations, alongside market demand to reduce inputs, has resulted in a strong driver for innovation to reduce chemical inputs (e.g., via integrated pest management). Anticipation of this should act as a filter on available innovations for compatibility with pesticide-reducing techniques.

With 40% of water pollution in England stemming from agriculture and rural land management, it is unsurprising that farmers are subject to several water-related regulations. English water regulations are drafted by the Department for Environment, Food & Rural Affairs (Defra) and enforced by the Environment Agency.[14,15]

Political pledges to address water-quality concerns through automatic fines of water companies and independent monitoring of outlets create a regulatory headwind that could eventually see monitoring requirements placed on farmers.[16] In addition, irrigators are subject to licensing requirements that require evidence of efficient water use. Innovations should therefore facilitate compliance with existing and potential future regulations through efficient water use that minimizes the risk of polluting runoff.

ADOPTION FACTORS

Economic factors can constrain innovation adoption. For example, the ability of soft fruit farmers to adopt high-cost innovations will be limited by access to financing (debt versus equity-based), the terms of the farm holding (owner occupied, wholly tenanted, or mixed tenure), and the ability to forecast and afford ongoing costs. Thus, any technology solutions must be low-cost in both CAPEX and OPEX.

Technical literacy can impede strawberry cultivators' adoption of agri-tech solutions. For example, after implementing a new irrigation system, growers must have extensive knowledge of irrigation methods (drop, soaker hose, micro-sprinklers, or overhead sprinklers), equipment (water abstraction, distribution, pumping, pump controls, and electrical controls), installation, and ongoing maintenance to create an optimal solution for their crop. Accessing relevant expertise externally presents a time and financial cost that most farmers can ill afford.

The regulatory environment, such as existing efficiency requirements for irrigators and government water management grants, can also impact affordability and thus implementation of suitable innovations. For example, Wicks Farm in East Sussex, a specialist strawberry grower, received UK £250,000 (about US $318,447) toward construction of a 32,000-cubic-meter reservoir to reduce water usage and serve as a local flood defense.[17] Grants such as this, although beneficial for this single farmer and geography, are dependent on sufficient government finances that are under continuous pressure from competing calls for taxpayer money. This pressure creates a credible risk that government support will be reduced or withdrawn, threatening uptake of agricultural innovations by farmers dependent on this financial assistance.

CASE STUDY 2: OASIS FARMERS

Small and medium-sized oasis farmers in the Draa Valley face increasing challenges due to water scarcity, with Morocco ranking among the world's most water-stressed countries. Large industrial farmers draw more water due to their access to advanced irrigation equipment subsidized through the Green Morocco Plan while oasis farmers struggle for access due to land fragmentation and challenges navigating the bureaucratic processes. Choosing the right technology to support oasis farmers is a complex exercise that requires consideration of both ecosystem factors and adoption constraints.

ECOSYSTEM FACTORS

Climate conditions in the Draa Valley are hostile and uncertain, requiring smart, secure, predictive technologies. Droughts and aridity, coupled with a decrease in already-irregular rainfall (ranging from 50 to 2,000 mm/year), exacerbate water scarcity. The situation is further complicated by the low quality of available water maps. The main water source is the El Mansour Eddahbi dam, but its annual releases are no longer sufficient, and its storage capacity is expected to fall from 583 million cubic meters in 1991 to below 250 by 2050.[18]

Soil health and management presents another challenge. Almost a third of the soil has become arid, with degradation increasing downstream of the dam. Erosion and increasing salinity are two other serious concerns.

> **THE REGULATORY ENVIRONMENT CAN RESTRICT THE FIELD OF SUITABLE INNOVATIONS**

Water laws and regulations are limited, with no mechanism to control groundwater pumping in the region, even though Morocco launched policies to limit groundwater overdrawing in 2009 through the National Water Strategy and National Water Plan. Compartmentalization among government sectors has hindered the development of effective solutions for water-related issues like groundwater depletion. Grassroots organizations play a crucial role in governing groundwater, focusing on local control to protect "their" aquifer from overexploitation. These community-led efforts involve crafting and enforcing local rules to manage water resources sustainably, ensuring long-term availability for local needs.[19]

ADOPTION FACTORS

Economic challenges include the fact that a significant portion of oasis farmers rely mainly on informal financial services, as the Moroccan banking sector finances only 17% of the capital required for agriculture. The government has invested in water-intensive commodities, equipping large farms with drip irrigation, storage basins, or solar-powered well systems rather than supporting the date palm oasis. However, new projects driven by the International Fund for Agriculture Development (IFAD) are emerging that may promote access to appropriate and sustainable financial services.

Technology literacy is a considerable constraint for oasis farmers, characterized by incomplete databases, technological illiteracy, and insufficiently democratized solutions. Additionally, youth engagement in oasis farming is decreasing, leaving mainly aging men who are unfamiliar with digital tools. Initiatives are in place to increase technology literacy, including the Crossroads of Initiatives and Agroecological Practices center.

Logistical and economic security factors are another key constraint for oasis farmers. Recently, technologies like drip irrigation or water basins have been introduced but with a focus on industrial players. Oasis farmers rely on crumbling wells that become riskier when water is pursued at greater depths. Another disadvantage is the fragmented land, which presents challenges to drip irrigation and requires tailored technology for successful well design.

AI TO THE RESCUE

The UK Agri-Tech Centre has been considering emerging opportunities for AI tools to support innovation adoption decisions. ADL has invested in two proprietary tools that can facilitate tailored identification of sustainable solutions to address specific agricultural use cases.

The first tool can determine and source data for the ecosystem factors from the numerous variables that might affect what technology to pick. The second tool can incorporate this data with specific use case and adoption variables to search for optimal technologies. These tools can help farmers sift through vast amounts of macro and microeconomic factors, regulations, and farm-specific challenges such as the ones highlighted in the two case studies.

UK Agri-Tech Centre's research found that advances like using ultra-fine bubbles (UFBs) in irrigation can help minimize water and chemical use.[20] UFBs possess unique properties such as high longevity and the ability to carry gases and surface adherents. A recent study found that UFBs improved strawberry crop yields while reducing potassium fertilizer requirements by 30% compared to levels using traditional drip irrigation.[21] Without AI horizon-scanning and search tools, this innovation would likely have been overlooked by farmers relying on traditional identification approaches.

In Morocco, ancestral risk management methods, such as agricultural diversification through livestock, are insufficient to address the recurrence of droughts and heat waves.[22] ADL's toolset can help identify relevant innovative risk management instruments, underpinning so-called climate-smart agriculture practices. One example is Azud, a Moroccan company that makes drip irrigation systems designed to improve water efficiency while protecting against clogging and offering resistance to UV degradation, key considerations for Moroccan farmers.

LOOKING TO THE FUTURE

Although AI tools can save stakeholders considerable time and money, expertise is required to craft effective prompts and use cases to interrogate the tools effectively. Nevertheless, with the rapid pace of innovation in AI, we envision a future where the two tools discussed here are combined into a single app-based interface with enhanced usability enabled by automatic geo-specific inputs such as climate, geopolitics, and regulations.

Such democratized access to information could equip farmers throughout the world to quickly gain visibility of suitable innovations to help them address specific challenges, enabling them to adopt technologies for profitable, sustainable farming.

The value proposition for agri-tech extends beyond farmers to investors, innovators, and regulators. Investors will benefit from knowledge of established and nascent technologies for investment (or to prepare for potential threats to existing investments). Innovators will benefit from visibility into key trends, uncertainties, and needs in farming alongside the current technology solutions to meet these, helping them identify "white spaces" to pursue. Regulators will benefit from an awareness of technologies that can facilitate their overarching goals and validate the feasibility of the regulations they enforce.

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REFERENCES

1 Holden, Joseph, et al. "Farming and Water 1: Agriculture's Impacts on Water Quality." The UK Water Partnership/Global Food Security, accessed July 2024.

2 "UN Calls for Urgent Action to Feed the World's Growing Population Healthily, Equitably and Sustainably." Press release, United Nations (UN), 19 April 2021.

3 "Global Organic Farming Market Growth 2024, Forecast to 2033." The Business Research Company, 17 January 2024.

4 "UN World Water Development Report: Water for Prosperity and Peace." UN Educational, Scientific and Cultural Organization (UNESCO), 26 February 2024.

5 Taft, Hessy L. "16 - Water Scarcity: Global Challenges for Agriculture." *Food, Energy, and Water: The Chemistry Connection*, 2015.

6 "How to Feed the World in 2050." Food and Agriculture Organization of the UN (FAO), accessed July 2024.

7 Rossi, Rachele. "Irrigation in EU Agriculture." European Parliament, December 2019.

8 Michel, David. "Water and Food: How, When, and Why Water Imperils Global Food Security." Center for Strategic & International Studies (CSIS), 16 October 2023.

9 Tongesayi, Tsanangurayi, and Sunungurai Tongesayi. "13 - Contaminated Irrigation Water and the Associated Public Health Risks." *Food, Energy, and Water: The Chemistry Connection*, 2015.

10 Lumley, Liz. "Agriculture Is Fast Becoming a Growth Market for Fintech." The Banker, 19 June 2024.

11 "Modern Agriculture Has Many Complex Challenges." Syngenta Global, accessed July 2024.

12 "United Kingdom Berries Market Size." Mordor Intelligence, accessed July 2024.

13 "British Berry Growers — Written Evidence (HSI0054)." UK Parliament, 8 April 2023.

[14] "Water and Sewerage Companies in England: Environmental Performance Report for 2020." UK Environment Agency, 14 January 2022.

[15] Department for Environment, Food & Rural Affairs, Environment Agency, and Steve Barclay. "Unlimited Penalties Introduced for Those Who Pollute Environment." Gov.UK, 11 December 2023.

[16] "Change: Labour Party Manifesto 2024." UK Labour Party, accessed July 2024.

[17] Wells, Izzie. "Water: How We've Helped Farmers Reduce Their Usage and Tackle Pollution." Gov.UK, 3 May 2024.

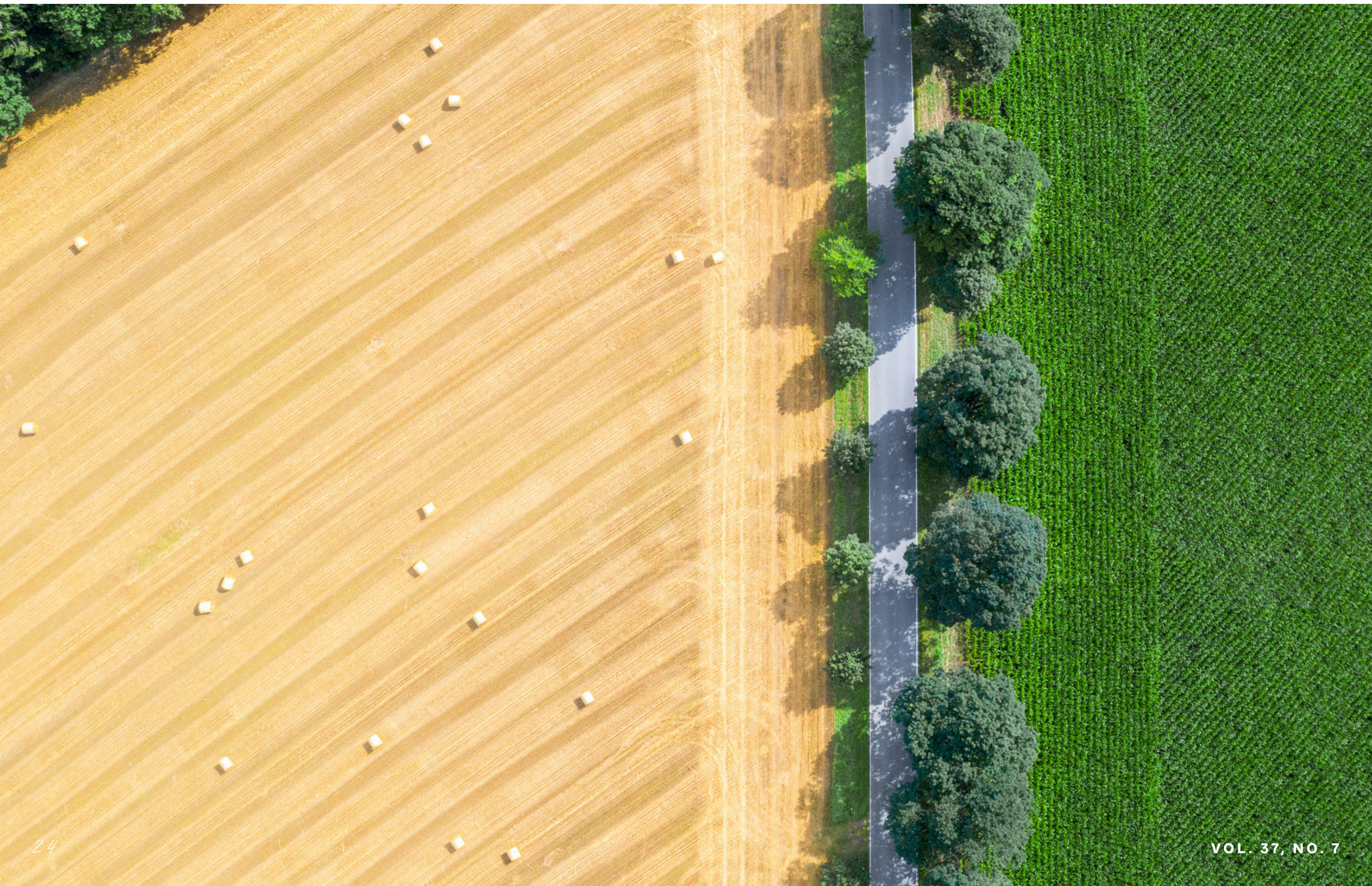
[18] Khebiza, Mohammed Yacoubi. "Environmental Vulnerability to Climate Change and Anthropogenic Impacts in Dryland (Pilot Study: Middle Draa Valley, South Morocco)." *Journal of Earth Science & Climatic Change*, January 2014.

[19] Bossenbroek, Lisa, et al. "Watermelons in the Desert in Morocco: Struggles Around a Groundwater Commons-in-the-Making." *Water Alternatives*, Vol. 16, No. 1, 2023.

[20] "Exploring the Benefits of Ultra-Fine Bubbles in Agriculture." Crop Health and Protection (CHAP), accessed July 2024.

[21] Wang, Jian, et al., "Micro-Nano Bubble Water with Potassium Fertigation Improves Strawberry Yield and Quality by Changing Soil Bacterial Community." *Rhizosphere*, Vol. 28, December 2023.

[22] "Moroccan Farmers Search for Solutions in the Face of Climate Change." World Bank Group, 20 December 2023.



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AN INTEGRATED APPROACH TO SUSTAINABLE, CLIMATE-RESILIENT AGRICULTURE

Authors

Vijaya Lakshmi and Jacqueline Corbett

The agriculture sector faces numerous challenges from climate change and global warming. Climate catastrophes have degraded billions of hectares of land and depleted water reservoirs, resulting in greater use of chemicals and overexploitation of natural resources.[1] Meanwhile, emissions from farm activities contribute considerably to global warming. The recursive cause-and-effect relationship between agriculture and climate change makes it increasingly difficult to achieve the goals of food security and sustainable agriculture.[2]

AI is expected to transform the agricultural sector. Farm organizations can use AI-based tools to manage resources more efficiently and support climate resilience. Climate-resilient agriculture (CRA) practices aim to enhance the long-term health of agricultural systems and the social systems that depend on them by combining traditional agricultural knowledge with modern techniques.[3]

The capacity of AI to analyze data on weather conditions, soil conditions, and crop genetics can improve CRA practices by facilitating the development of climate-resistant seeds and enabling informed decisions on harvesting and planting times, water management, and chemical use.[4] However, the transformation to CRA practices is hindered by complex sociocultural, technical, and ecological barriers.[5,6]

In this article, we discuss the barriers smallholder farmers face in using AI tools to manage the impacts of climate change on arable farming (crops and fruit) practices. Smallholder farmers represent 95% of the world's farmers and produce 45% of global food.[7] They rely on rain-fed agriculture (little or no irrigation), cultivate in marginal areas, lack access to technical or financial support, and face increased vulnerability due to climate change.[8] We present three case studies from India, highlighting how these farm organizations leverage their traditional knowledge and practices to overcome socio-technological-ecological barriers and maximize the value of AI tools for CRA.

CRA & AI

AI-based technologies are increasingly being harnessed to develop agricultural practices that can more easily adapt to climate change. Technologies such as intelligent robots and drones, deep learning, and generative AI are being used to create resilient seed varieties, predict climate patterns, and recommend crop varieties based on climate forecasts.[9]

> **THE CAPACITY OF AI TO ANALYZE DATA ON WEATHER CONDITIONS, SOIL CONDITIONS & CROP GENETICS CAN IMPROVE CRA PRACTICES**

Intelligent technologies are also being employed to monitor environmental conditions that contribute to the spread of diseases and pests, which are further worsened by climate change. For example, by analyzing soil moisture levels and weather forecasts, AI-based tools can optimize irrigation schedules to conserve water while ensuring that crops receive the optimal amount of water, even in water-stressed areas.[10] Further, by integrating AI with other agricultural technologies, such as electric tractors and drip irrigation, farmers can use critical resources, including fertilizers and pesticides, more efficiently to minimize soil degradation and harmful environmental impacts.[11]

TRADITIONAL KNOWLEDGE IN CRA

Traditional farming knowledge, developed over generations, includes a location-specific understanding of climate, plant varieties, soil fertility, and seasonal weather calendars.[12] This includes experience and wisdom achieved through direct (own experiences) or indirect (others' experiences) observations. Smallholder farmers regularly rely on traditional knowledge in their agricultural operations as a way to ensure agricultural diversity, meaningful livelihoods, food security, ecological health, and biodiversity.[13]

For instance, farmers can use traditional knowledge formed from observations of bird behavior, soil conditions, and atmospheric events to predict precipitation and weather patterns. This knowledge can inform crop selection, planting times, and harvesting activities. Other traditional practices, such as seed storage in facilities on farms and homes, help preserve viable seeds for food security and biodiversity.

Despite the value of traditional knowledge in dealing with short-term weather variability, severe climate change effects are threatening long-term efficacy and increasing the need for support from modern information technologies.[14] Traditional knowledge combined with AI and real-time data enables better decision-making as well as enhanced prediction, planning, and preparation for potential climate and weather-related shocks to protect communities and agricultural systems.[15] Still, to take full advantage of AI-based technologies, farm organizations must overcome sociocultural, technical, and ecological barriers.[16]

AI IN AGRICULTURE: 3 CASE STUDIES

We have researched the use of AI in sustainable agriculture over the past three years, speaking with farmers and IT providers to understand their challenges and experiences. Our conversations reveal how farm organizations integrate traditional farming knowledge with AI-based tools for climate-smart crop management and sustainable agricultural outcomes. Below, we present three exemplar cases (pseudonyms have been used for the real farm names).

1. ORGANIC ORCHARD

Organic Orchard is located in the western part of India. This farm grows fruit and operates a plant nursery. The owner is passionate about organic agriculture and promotes organic farming practices that prioritize soil health and fertility.

In 2021, Organic Orchard implemented an AI-based disease-detection app to support low- or no-chemical fruit plantation management. Using the application involved uploading photos of infected plants to the app to receive AI-generated diagnoses of potential diseases and nutrient deficiencies, along with disease management recommendations.

The owner explained: "The app suggests everything: chemical management, biological management, and mechanical management. Our focus is on organic farming, so whatever information is available regarding organic farming, we apply that." Once Organic Orchard received information on nutrient deficiencies from the app, workers supplemented the app's recommendations with traditional ways of fertilizing (e.g., oilseed cake to treat nitrogen deficiencies).

Organic Orchard actively created community awareness and promoted the benefits of the app, including increased productivity and reduced chemical application. However, some farm workers and others in the community were wary of using the app. They perceived it as a threat to their long-held beliefs and local farming practices because it did not provide information on fruits commonly grown in the area. These perceived threats were exacerbated by a lack of engagement from government experts who were responsible for advising farmers on best practices for crop management and pest and disease control.

One participant pointed out: “Technology should be made to reach farmers’ fields and is the responsibility of the extension workers. But you know about the government officers (extension workers); they do not come out of their office rooms.”

To build confidence in the technology, Organic Orchard’s owner organized meetings to share his experience of integrating technology with traditional knowledge and practices. He explained: “Because we work in the fields, we have an idea about the weather. We know pest attack is probable when the clouds gather. So, we already know, and we get confirmation through the app, and we feel that we are going in the right direction.”

Over time, Organic Orchard combined traditional practices like observing atmospheric events with the AI-based tool for disease detection to improve decision-making and support CRA by limiting the application of chemical fertilizers and promoting organic farming to restore soil health.

2. CROP FARM

Crop Farm is situated in the hilly northern region of India, where it grows commercial trees, wheat, and seasonal vegetables. In the past, Crop Farm was successful in applying traditional knowledge gained from observing atmospheric conditions and estimating rainfall. However, changing weather patterns and decreased precipitation increased water problems in the already water-scarce area, rendering traditional knowledge insufficient for effective crop management.

For example, Crop Farm traditionally fertilized its crops 30 days after plantation, but shifting rainfall patterns affected fertilization efficiency, causing low yields. Similarly, the farmer followed the traditional method of harvesting wheat at the end of winter and leaving the harvested wheat grains in the fields to dry. Recently, unpredictable weather and sudden rainfall frequently damaged the grains.

Crop Farm began using AI-based weather-prediction apps to get rainfall estimates in an effort to better manage water levels in the fields. The goal was to better prepare the fields for fertilization, protect threshed grains from damage, and arrange for alternative irrigation sources as required. One farm worker reported: “At times, after threshing, the wheat was kept in the fields, and suddenly it would rain at night, and the wheat would be wet and damaged. Now, we work by watching the forecast. Harvesting and threshing are mostly done after consulting the weather predictions.”

During the implementation and use of the apps, Crop Farm encountered issues due to the remote location of the village. Lack of Internet connectivity and technology infrastructure (e.g., weather stations) created problems with weather-prediction accuracy and efficacy for the apps. Because of these technical barriers, Crop Farm returned to using traditional knowledge of weather predictions for managing farm activities. A farm worker pointed out: “When the temperature has risen to 48-49 degrees Celsius, then usually we get rain after two to three days to lower the temperature. So, we have some of these ways to predict the weather.”

Based on traditional knowledge and observations of the natural rain cycle, Crop Farm’s owners understood the importance of capturing and storing rainwater for irrigation in case of delayed monsoons. They combined their experience and reasoning with app-based weather predictions to adapt to evolving weather patterns resulting from climate change and prioritized rainwater harvesting, as one of the workers explained: “For a long time, there used to be much rain in November–December here, but this year November [and] December were dry, and it only rained in January. So, I have built a temporary dam under my house, where the rainwater gets collected, then the stored water is used for irrigation.”

This combined learning helped them better understand changing weather patterns, implement sustainable and efficient water management methods, and reduce soil erosion.

3. CEREAL FARM

Cereal Farm, a family farm in the northeastern region of India that grows cereals, also faces the impacts of climate change. Once known for its high fertility and ample rainfall, the region now experiences droughts. Climate change has led to unpredictable weather patterns, sudden and delayed rainfall, and hailstorms — leading to reduced productivity and crop quality.

To tackle these issues, Cereal Farm deployed an AI-based crop advisory app that provides weather predictions, planting and harvesting recommendations, and disease-detection and remedial recommendations. Simultaneously, as recommended by the app, the owners switched to drought-resistant hybrid maize seeds to enhance productivity and use.

However, farmers expressed concerns about problems like unreliable weather predictions, failure of suggested recommendations for fertilizer applications, unsuitability of hybrid seeds to local conditions, and loss of local seed varieties. One farmer shared: "Our ancestors saved some of the harvest to be used as seeds in the next season. When the technology came, hybrid seeds were suggested to increase crop yield. But when harvesting season came, we realized the seeds hadn't grown properly. So, people switched from the hybrid seeds to the native seeds they used to collect every year, which led to the betterment of seed quality every year.

Despite using the app, they continued to rely on their intuition, experiences, and traditional knowledge. One farmer said: "Traditional knowledge has its own importance, but when it comes to dealing with climate change, it will be important to use technology and take advantage of it. Both should be considered side by side."

The combination of traditional knowledge with recommendations from the crop advisory app was the best strategy for planting and harvesting decisions at Cereal Farm. As another farmer put it: "The things that have been carried out through generations about what should be planted in which season, how the field should be prepared, and how things should be done, these are the traditional knowledge. What new do we add to this? When will it rain? Should we irrigate or not? When should the crop be harvested, and where should the products be sold? This is what is new, and with app tools, we get to know how these should be done."

COMMON BARRIERS TO AI USE IN CRA PRACTICES

These case studies show the range of sociocultural, technical, and ecological barriers farmers face in using AI for CRA:

- **Sociocultural barriers** — challenges related to the social and cultural contexts in which AI-based technologies are deployed:
  - Insufficient knowledge of AI within farm organizations, shortage of domain experts, and inadequate engagement of stakeholders (e.g., government officers) can limit organizational awareness of the value and benefits of AI for CRA.
  - Culturally specific factors, such as community norms and practices and workers' reluctance to try new practices, can decrease AI's potential for CRA practices.
- **Technical barriers** — real and perceived problems associated with AI-based technologies and tools:
  - AI-based tools trained on global data and non-representative farm-specific data can lead to inconsistent and even conflicting predictions. These inconsistencies (e.g., weather predictions) can increase organizations' reluctance to use the tools.
  - A lack of technological infrastructure within rural farming regions (e.g., weather stations) can amplify prediction inaccuracies.
- **Ecological barriers** — arise from the dynamic conditions in the natural environment in which agricultural activities take place:
  - Lack of location-specific, contextual awareness of AI-based tools can create problems in achieving desired results because recommendations can fail in local conditions.
  - Reliance on AI-based technology for CRA practices (e.g., climate-resistant and hybrid seeds) can raise ecological risks of losing local seed diversity.

POTENTIAL OF CONJOINT LEARNING APPROACH FOR CRA

Overcoming the aforementioned barriers will require additional development of AI-based technologies. It will also require listening to — and learning from — agricultural workers. A conjoint learning approach that combines traditional knowledge with AI tools can enhance AI performance and help overcome the barriers discussed above. Specifically:

- **Traditional knowledge combined with direct observations can be useful in addressing technical barriers.** Climate change makes it difficult for AI tools to predict microclimatic shifts.[17] By incorporating local knowledge with satellite imaging and remote sensing, AI tools can provide more precise weather forecasting and improve adaptation of agricultural practices at a local scale.
- **Social networks, indirect observation, and the integration of traditional farming knowledge with AI can help resolve sociocultural barriers.** Traditional knowledge emphasizes cultural sensitivity and respect for nature, which can be integrated into AI tools to prevent bias and ensure cultural consciousness. Incorporating information on local culture, crop varieties, and languages through conjoint learning can increase trust in AI tools. It can also make AI tools relevant and useful for smallholder farmers who do not grow commodity crops or who practice organic or regenerative farming.[18]
- **When combined with traditional ecological knowledge, which includes the relationship between plants, animals, land, and people, AI-based tools are more context-aware.** By enhancing the understanding of ecological and atmospheric events, they can support better crop management, water and resource management, and chemical usage. Traditional ecological knowledge, when combined with AI can assist in ecological restoration by analyzing historical data, identifying native species, and predicting suitable areas for reforestation, habitat restoration, and ecosystem rehabilitation.[19]

By broadening the view of AI use in CRA from a technical perspective to a socio-cultural-technical-ecological one,[20] conjoint learning offers a more holistic way to advance AI-based tools for CRA and encourages more reflection on how agricultural practices can be adapted based on the vulnerabilities of a specific farming system.[21,22] Figure 1 presents a framework for understanding these relationships.

RECOMMENDATIONS

Conjoint learning offers ways to improve AI-based agricultural solutions, ultimately leading to better outcomes for CRA:

- Organic Orchard actively shared its successful experiences of conjoint learning in managing local crops with community members to raise awareness and build trust in AI-based systems.
- Crop Farm gained valuable insights into changing local weather patterns and used app-based predictions to add value to traditional farm practices.
- Cereal Farm combined its traditional ecological knowledge with app-based weather predictions to enhance planting and harvesting decisions.

To reap the full benefits of conjoint learning to enhance AI effectiveness for CRA, agriculture technology organizations should prioritize conjoint learning in their own activities, from development to deployment. This would involve understanding farmers' expectations for using AI to respond to climate change impacts and developing respectful ways to collect and organize traditional knowledge.

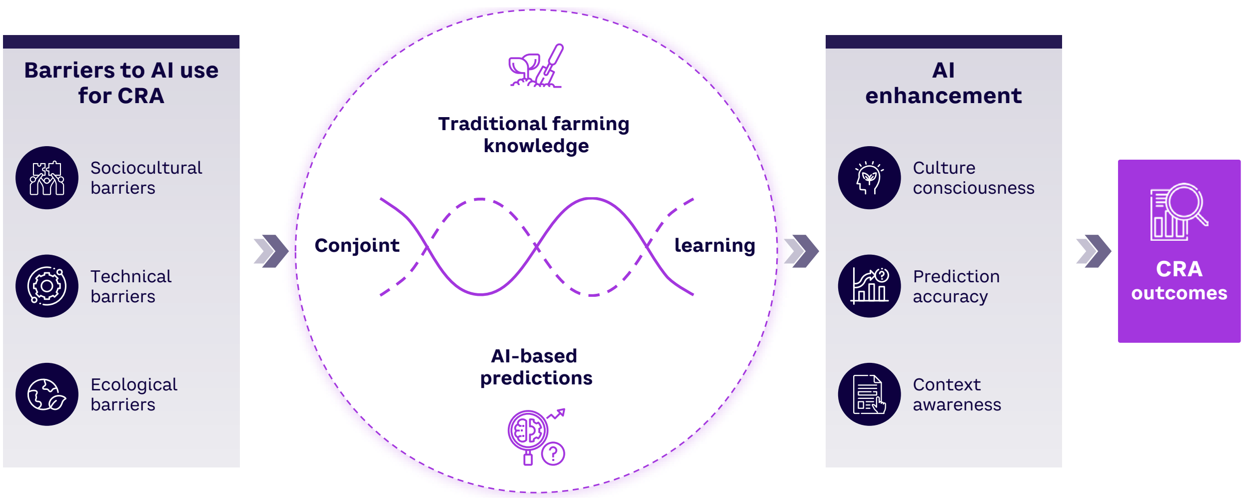

Figure 1. Conjoint learning approach to promote CRA (adapted from: Lakshmi and Corbett, 2023)

For example, to increase context awareness and prediction accuracies of AI-based technologies, the developers of the crop advisory app used by Cereal Farm organized monthly meetings with the farmers *in their fields* to collect real-time data. This helped the developers gain a deeper appreciation of farmers' needs and the value of their traditional knowledge.

A CONJOINT LEARNING APPROACH CAN LEAD TO MORE ACCURATE & INCLUSIVE AI SOLUTIONS

Policy makers and government agencies that bear responsibility for promoting and supporting CRA can also benefit from, and contribute to, conjoint learning. As we saw with Organic Orchard, lack of involvement from government representatives can impede the adoption of technology by smallholder farmers, delaying CRA goal achievement. Note that as policy makers start to use AI-based tools to support their work in devising climate-resilience strategies, they will need to integrate their own traditional knowledge.

Engagement among various stakeholders (farmers, developers, and policy makers) can create a conducive environment for efficient development and use of AI-based tools in addressing climate change impacts:

- Farming organizations should establish connections with other farmers and domain experts, gather information about agricultural innovations, collaborate with technology providers in improving AI-based solutions, and embrace innovation in their farming practices.
- Agricultural AI providers should engage in collaborative research to understand farmers' needs, develop ways to weave traditional knowledge into their solutions, and involve farmers in development processes to enhance AI-based tools and support effective deployment and implementation.
- Policy makers and research organizations should educate farming organizations on the use and benefits of AI, create farming knowledge hubs, and facilitate open discussions with technology providers to promote awareness of and trust in AI-based tools.

CONCLUSION

When combined with traditional knowledge, AI-based technologies have the potential to address the sociocultural, technical, and ecological barriers of AI use for CRA. A conjoint learning approach can lead to more accurate and inclusive AI solutions, benefiting diverse cultures and farm environments. Operationalizing this approach will ensure the effectiveness of our response to the existential challenges of climate change.

REFERENCES

[1] Sartori, Martina, et al. "Remaining Loyal to Our Soil: A Prospective Integrated Assessment of Soil Erosion on Global Food Security." *Ecological Economics*, Vol. 219, May 2024.

[2] "Climate Smart Agriculture Sourcebook." Food and Agriculture Organization of the United Nations (FAO), accessed July 2024.

[3] Okoronkwo, David John, et al. "Climate Smart Agriculture? Adaptation Strategies of Traditional Agriculture to Climate Change in Sub-Saharan Africa." *Frontiers in Climate*, Vol. 6, January 2024.

[4] Hall, Curt. "Sustainable, Intelligent & Connected: Electric Tractors for Precision Agriculture." Cutter Consortium Sustainability *Advisor*, 29 May 2024.

[5] Mana, Aali, et al. "Sustainable AI-Based Production Agriculture: Exploring AI Applications and Implications in Agricultural Practices." *Smart Agricultural Technology*, Vol. 7, No. 7664, February 2024.

[6] Lakshmi, Vijaya, and Jacqueline Corbett. "Using AI to Improve Sustainable Agricultural Practices: A Literature Review and Research Agenda." *Communications of the Association for Information Systems*, Vol. 53, 2023.

[7] Heldreth, Courtney, et al. "What Does AI Mean for Smallholder Farmers? A Proposal for Farmer-Centered AI Research." *Interactions*, Issue 28, No. 4, July–August 2021.

[8] Duchicela, Sisimac A., et al. "Microclimatic Warming Leads to a Decrease in Species and Growth Form Diversity: Insights from a Tropical Alpine Grassland." *Frontiers in Ecology and Evolution*, Vol. 9, September 2021.

[9] Mana et al. (see 5).

[10] Heldreth et al. (see 7).

[11] Duchicela et al. (see 8).

[12] Abbasi, Rabiya, Pablo Martinez, and Rafiq Ahmad. "The Digitization of Agricultural Industry — A Systematic Literature Review on Agriculture 4.0." *Smart Agricultural Technology*, Vol. 2, December 2022.

[13] Abbasi et al. (see 12).

[14] Imoro, Ziblim Abukari, et al. "Harnessing Indigenous Technologies for Sustainable Management of Land, Water, and Food Resources Amidst Climate Change." *Frontiers in Sustainable Food Systems*, Vol. 5, August 2021.

[15] Imoro et al. (see 14).

[16] Lakshmi and Corbett (see 6).

[17] Duchicela et al. (see 8).

[18] Martinescu, Livia. "AI for Climate Change: Using Artificial and Indigenous Intelligence to Fight Climate Change." Oxford Insights, 4 December 2023.

[19] Abbasi et al. (see 12).

[20] Rahman, Saeed, Natalie Slawinski, and Monika Winn. "How Ecological Knowledge Can Catalyze System-Level Change: Lessons from Agriculture & Beyond." *Amplify*, Vol. 1, No. 5, 2022.

[21] Lakshmi and Corbett (see 6).

[22] Zheng, Hongyun, Wanglin Ma, and Quan He. "Climate-Smart Agricultural Practices for Enhanced Farm Productivity, Income, Resilience, and Greenhouse Gas Mitigation: A Comprehensive Review." *Mitigation and Adaptation Strategies for Global Change*, Vol. 29, No. 8, March 2024.

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LEVERAGING AI TO FOSTER CLIMATE-RESILIENT & SUSTAINABLE AGRICULTURE

Author

San Murugesan

Global agriculture, the bedrock of our existence, faces unprecedented challenges from climate change, soil degradation, and water scarcity, affecting yields and threatening food security and sustainability. Escalating temperatures, unpredictable weather patterns, and environmental degradation endanger farmers' livelihoods, our societal fabric, and the biosphere.

The agricultural sector's contribution to the global economy has plummeted from 10% in the 1960s to below 5% in 2020, underscoring the crisis.[1] With the world's population expected to reach 9.7 billion by 2050, sustainably increasing food production is paramount.[2]

Recent disruptions such as the Russia-Ukraine and Israel-Hamas wars, the pandemic, and ongoing environmental dangers highlight the fragility of our global food system. Without swift, decisive action, food prices could rise and supply chain disruptions could worsen.

Addressing in unison the three challenges of feeding a growing population, ensuring a decent livelihood for farmers, and safeguarding the environment is essential to sustainable progress. Because farmers constitute a large portion of our population, particularly in developing countries and rural areas, agricultural advances and productivity gains shouldn't come at the expense of their livelihoods. And, of course, agricultural practices shouldn't be detrimental to the environment.

THE ROLE OF AI

Food and agriculture were highlighted for the first time at the 2023 *United Nations Climate Change Conference (COP 28)*. In this landmark event, more than 130 countries signed a "Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action" to prioritize their food systems in their national strategies to combat climate change, signaling a global commitment to sustainable agriculture.[3]

Technological advances, particularly in AI, offer innovative and cost-effective solutions to boost agricultural productivity while mitigating economic and environmental risks. Technology can also bolster traceability in the agri-food chain, helping growers and distributors meet rising consumer demand for transparency about the origin of their food.

AI is a powerful tool with the potential to transform agriculture into a climate-resilient and sustainable sector. This article explores how AI, supported by the Internet of Things (IoT), cloud computing, and smartphones, can address the challenges posed by climate change and foster sustainable agricultural practices.

> **AI IS A POWERFUL TOOL WITH THE POTENTIAL TO TRANSFORM AGRICULTURE INTO A CLIMATE-RESILIENT & SUSTAINABLE SECTOR**

AGRICULTURE 4.0

Like manufacturing and transport, agriculture has evolved over centuries. It is now in its fourth phase (Agriculture 4.0), which features improved crop yield, optimal resource allocation, and nutrient management. This phase's technology-enhanced agriculture presents myriad ways to foster a journey toward climate-resilient, sustainable farming.[4] Below are the key technologies driving modern agriculture:

- **AI and predictive analytics.** Machine learning (ML) and predictive analytics use data from satellite imagery, weather forecasts, and soil sensors to analyze crop health, potential yields, and the best times for planting, irrigating, and harvesting. They also predict pest invasions and disease outbreaks, enabling precise treatments that minimize crop damage and reduce chemical usage. Predictive analytics assist in soil management by optimizing irrigation and fertilization schedules. Generative AI (GenAI) platforms like ChatGPT can assist farmers by providing both general recommendations and specific information on their crops (see sidebar "GenAI in Agriculture").
- **Remote sensing and drones.** High-resolution cameras and drone sensors capture detailed aerial images of crops and plants that AI can analyze to monitor crop health, identify pests and diseases, and evaluate crop maturity. This minimizes waste by helping farmers precisely apply water, fertilizer, and pesticides and increases yields.
- **Robotics and automation.** Autonomous robots can perform labor-intensive tasks like planting, weeding, and harvesting. They distinguish weeds from crops and selectively harvest ripe produce without causing damage. This precision reduces labor costs, saves time, and minimizes crop damage, resulting in healthier fields and increased yields. Robots can operate continuously, extending fieldwork hours.
- **IoT and smart farming.** IoT sensors gather real-time environmental data from soil moisture sensors, weather stations, and livestock health monitors. Analyzing this data helps optimize irrigation schedules, automate operations, and improve resource efficiency. Soil moisture sensors ensure optimal water usage, and livestock tracking devices offer early warnings about potential illnesses. IoT actuators can be remotely controlled to irrigate crops or apply pesticides when and where needed.
- **Cloud computing.** Cloud services host applications, data storage, and data and information-sharing facilities for the farming industry and the food supply chain. Farmers' adoption of smartphones gives them access to these services.

Together, these technologies can transform agriculture into a data-driven, efficient, sustainable practice.

AI IN AGRICULTURE

AI and ML can empower agriculture by improving yield and resource use, minimizing waste, improving crop management, and ensuring that produce meets consumer demand.

PRECISION AGRICULTURE

AI enables precise monitoring of soil health, water usage, and crop conditions through sensors and drones. John Deere's See & Spray system (developed by Blue River Technology) uses computer vision to identify and target individual weeds with herbicides, increasing crop yield, reducing chemical use (by up to 90% in cotton fields[5]), and minimizing environmental impact while improving efficiency. John Deere reports a reduction in herbicide use by up to 77% compared to traditional broadcast spraying methods, resulting in significant cost savings and reduced environmental impact.[6] This targeted approach also contributes to improved crop health and higher yields.

AUTOMATED IRRIGATION SYSTEMS

Companies like CropX use AI algorithms to analyze soil moisture data obtained via sensors and automatically control irrigation systems. CropX reports a 25%-50% reduction in water usage while maintaining or improving crop yields due to optimized irrigation scheduling.[7] In addition, the CropX system is saving energy, fertilizers, and pesticides — reducing greenhouse gas (GHG) emissions and soil pollution on a large scale.

GENAI IN AGRICULTURE

GenAI, a relatively new player in the AI landscape, has received enormous interest from developers and users and is revolutionizing business, healthcare, and education, among other sectors. By harnessing the power of GenAI, farmers can enhance productivity, sustainability, and profitability, ensuring a stable food supply for the growing global population. Below are some ways GenAI could foster sustainable agriculture:

- **Crop yield prediction and optimization.** GenAI models can analyze historical data, weather patterns, soil characteristics, and crop traits to forecast yields with remarkable precision. These insights lead to informed decisions about planting, irrigation, and harvesting, resulting in increased yields, reduced resource wastage, and mitigated risks. GenAI can help farmers adapt to climate change and determine optimal crop choices and water resource management strategies.
- **Resource allocation and management.** GenAI can assist in resource planning and procurement, ensuring efficient resource use and minimizing waste.
- **Market analysis.** Farmers must stay informed about market trends to secure the best prices for their produce. GenAI can provide farmers with real-time information on market trends, prices, and demand, helping them better synch with markets and more skillfully manage risks.
- **Supply chain management.** GenAI can optimize agricultural supply chains, helping farmers and traders transport crops to market more efficiently, reducing waste and increasing profits. The technology helps farmers more easily steer around weather-related disruptions and other transport problems.
- **Pest and disease management.** GenAI is revolutionizing pest and disease management by enabling real-time monitoring and early detection. By analyzing visual data from drones or sensors, AI identifies subtle crop changes, allowing for targeted interventions and reducing the need for broad spectrum chemical treatments.
- **Farmer training.** GenAI can create personalized training modules tailored to farmers' needs, helping them learn new skills and techniques.
- **New seed breeding and fertilizer development.** GenAI supports gene editing to help researchers develop climate-resilient crops and environmentally friendly fertilizers (e.g., microbial fertilizers), as well as enhance produce quality. For instance, it can identify genes that show specific traits of interest (e.g., growth in hotter climates or pest resistance) and combine these traits to create seeds designed to foster more sustainable agriculture.
- **Farmland management.** Using vast amounts of data, GenAI can provide practical insights into farmland activities such as crop rotation and yield prediction.
- **Farming advisors.** Chatbots can serve as 24/7 advisors accessible via a smartphone in the farmer's preferred language. They can help farmers retrieve information and recommendations on resources like water and fertilizers, reducing waste and environmental impact. For example, WhatsApp's Telugu-language chatbot, developed as part of India's Saagu Baagu initiative, provides farmers with timely suggestions tailored to the maturity stages of their crops.

CROP MANAGEMENT, YIELD PREDICTION & OPTIMIZATION

AI-powered satellite imagery systems monitor crop growth, detect diseases, and recommend interventions. This proactive approach reduces losses and maximizes yield sustainably. For example, companies like Agrible and Descartes Labs use ML to analyze satellite data and provide farmers with insights into crop health, yield estimates, and potential issues like pests or diseases.[8] Farmers can make data-driven decisions on irrigation, fertilization, and pest management.

A study published in *Computational Intelligence and Neuroscience* demonstrated an AI system's capability to detect apple scab, a typical apple tree disease. Using a neural network trained on a data set of apple leaf images, the system achieved an impressive 95% accuracy in identifying disease presence.[9]

ROBOTICS & AUTOMATION

AI-empowered robots could automate many labor-intensive agriculture activities, including preparing the soil, planting seeds, removing weeds, and harvesting. For example, autonomous weeding robots developed by FarmWise identify and remove weeds from crops without damaging plants. These robots offer benefits such as labor savings, reduced herbicide reliance, and improved weed control. Through better weed detection and removal, weeding robots reduce herbicide use, lowering costs and reducing environmental impact.[10]

MARKET FORECASTING & PRODUCE SUPPLY CHAIN MANAGEMENT

AI empowers supply chains by predicting demand, optimizing logistics, and reducing food waste, resulting in sustainable consumption patterns and decreased GHGs. For example, AgShift uses AI to assess the quality and value of harvested crops, helping farmers make better pricing and market timing decisions. Through improved quality assessment, AgShift solutions reduce post-harvest loss and food waste, ensuring optimal use of harvested produce.[11]

CLIMATE PREDICTION & ADAPTATION

ML algorithms analyze climate data to predict weather patterns and optimize planting schedules. AI-driven models help farmers adapt cultivation practices to changing conditions, improving resilience against climate variability.

DATA-DRIVEN DECISION-MAKING

AI-driven insights are transforming farming practices by enhancing data-driven decision-making. For example, Climate FieldView leverages AI to give farmers actionable insights from various data sources, offering personalized planting advice, optimized seeding rates, and guidance on the best times to water and apply fertilizers and pesticides. The program can predict how variables, such as weather changes or planting densities, might affect crop yields. This predictive capability lets farmers make more informed decisions, increasing crop productivity and reducing resource waste.

IBM's Watson Decision Platform for Agriculture uses AI to analyze weather data, satellite images, and other inputs, providing farmers with actionable insights. The technology helps farmers precisely apply water, fertilizers, and pesticides, reducing overuse and runoff.

The World Economic Forum (WEF) is an excellent source for information on how data is transforming agriculture, including an article titled "How Is Agritech Helping to Optimize the Farming Sector?"[12] and one on how data-driven agritech services in Telangana, India, could add US $50-$70 billion to the agriculture sector by 2025.[13]

HUGE OPPORTUNITIES

Farmers can achieve significant efficiency gains and economic returns by leveraging AI-driven solutions while minimizing environmental impact. Indeed, AI presents unprecedented opportunities to build climate-resilient and sustainable agricultural practices. WEF elaborates on the benefits of AI in its article "Artificial Intelligence for Agricultural Innovation,"[14] and specific use cases are described in the sidebar "AI in Action: Enhancing Agricultural Practices."

However, concerted efforts by multiple stakeholders (governments, agritech companies, and farmers) will be needed to realize these opportunities. This may include subsidizing AI implementations and investing in agricultural AI R&D. To foster wider adoption, we recommend tailored education and training (e.g., Udemy courses) and the development of shared, trusted, open data platforms providing secure, role-based access to systems and stakeholders.

ADOPTION CHALLENGES

AI's true impact depends not on its vast potential but on large-scale adoption by farmers, smallholders, and large agricultural companies. Despite AI's potential to foster sustainable agriculture, there are several major challenges to widespread adoption:

- **Implementation costs.** Many AI solutions require up-front investment in equipment and software, which can be prohibitive for small-scale farmers or those with limited financial resources. The initial cost of adoption may outweigh the perceived benefits, especially if the ROI may not be realized for several years.

AI IN ACTION: ENHANCING AGRICULTURAL PRACTICES

The global AI in agriculture market, valued at $1 billion in 2022, is projected to grow at a CAGR of approximately 25% from 2023 to 2031.[1] Some use cases driving the market are:[2]

- **Precision farming.** AI-powered equipment like John Deere's uses sensors and GPS to optimize planting, watering, and fertilizing, increasing yields and reducing waste.
- **Crop and soil monitoring.** AI-driven aerial imagery from Taranis helps detect nutrient deficiencies and pest infestations early, improving crop health.
- **Predictive analytics for crop management.** Platforms like aWhere provide insights into weather patterns, helping farmers proactively manage crops.
- **Automated weed control.** Blue River Technology's robots precisely eliminate weeds, reducing herbicide use and environmental impact.
- **Livestock monitoring and management.** Connecterra's Ida uses sensors and AI to enhance herd health and productivity.
- **Agricultural drones.** DJI drones assess crop health and perform targeted spraying, saving time and resources.
- **Yield prediction and optimization.** Cropin analyzes farm data to predict yields and suggest optimizations.
- **Supply chain management.** IBM's Food Trust increases transparency and reduces waste in the food supply chain.
- **Greenhouse automation.** Motorleaf's systems optimize greenhouse climates for better crop growth.
- **Gene editing for crop improvement.** Benson Hill uses AI to identify traits for improved crop sustainability and yield.
- **Pest and disease detection.** The Plantix app uses AI to detect pests and diseases early, enabling timely interventions.
- **Water management.** Arable provides irrigation recommendations based on climate and soil moisture data.
- **Market demand prediction.** AgriBORA predicts market demand to help farmers maximize profitability.
- **Satellite imagery for large-scale monitoring.** Planet Labs's satellite imagery helps farmers monitor crop health and environmental changes.
- **Automated harvesting systems.** Harvest CROO Robotics develops AI-driven strawberry-picking robots to address labor shortages and increase efficiency.

[1] Straits Research. "AI in Agriculture Market Size Is Projected to Reach USD 5.96 Billion by 2031, Growing at a CAGR of 25%." GlobeNewswire, 13 September 2023.

[2] "Top 15 Real-Life Use Cases for AI in Agriculture Industry." Redress Compliance, 7 March 2024.

- **Complexity and integration challenges.** AI technologies often require integration with existing farming practices, equipment, and data systems. The complexity of implementation and potential disruptions to established workflows can deter farmers from adopting these solutions.
- **Data privacy and security concerns.** AI applications in agriculture rely heavily on data collection and analysis, including sensitive information about crop yields, soil health, and farming practices. Farmers may have concerns about data privacy, ownership, and security when using AI-powered platforms and services.
- **Limited access and unreliable connectivity.** Many areas where agriculture is prevalent have limited access to reliable Internet connectivity and infrastructure essential for real-time data collection and analysis.
- **Tailoring to local contexts.** AI solutions must usually be tailored to local agricultural contexts, including specific crops, soil types, climate conditions, and farming practices. One-size-fits-all solutions are unlikely to effectively address the diverse needs of farmers.

In addition, Western technology and business models often don't apply in other geographies due to differences in scale. Western farms are typically larger than 1,000 acres, while farmers in India and many developing countries usually manage between two and 10 acres, often in different locations. Technologies designed for large-scale farms are not practical for smallholders.

To address these challenges, agritechs must focus on effective distribution and adoption rights. Village-level entrepreneurs (VLEs) play a crucial role in this process. Connecting VLEs with private capital is essential to driving social development and change. Furthermore, technology must be localized to meet the specific needs of these regions:

- **Lack of awareness and education.** Farmers may not be fully aware of the capabilities and benefits of AI technologies in agriculture. They may lack education and training on effectively integrating these technologies into their farming practices.
- **Resistance to change.** Farming is a traditional industry in which practices are often passed down through generations. Resistance to change and reluctance to adopt new technologies can be cultural and/or fear-based.

- **Risk aversion.** Farmers may be risk averse when adopting new technologies that could impact their livelihoods. The potential failure or disruption caused by adopting AI solutions may outweigh the perceived benefits for some farmers.
- **Regulatory and policy barriers.** Regulatory frameworks and policies related to AI adoption in agriculture vary across regions and countries. Uncertainty about compliance and regulations may create barriers to adoption.

A recent study in *Environmental Science & Policy* offers farmers' perspectives on options for and barriers to implementing climate-resilient agriculture and implications for climate adaptation policy.[15]

RECOMMENDATIONS

To promote the widespread adoption of AI in agriculture, stakeholders such as governments, technology providers, research institutions, and agricultural organizations must work together to address challenges related to cost, education, infrastructure, regulation, and cultural acceptance.

The WEF initiative "AI for Agriculture Innovation (AI4AI)" is designed to advance the global agenda of digital agriculture by scaling up emerging technologies and encouraging public-private partnerships. The initiative aims to impact 1 million farmers globally by 2027. Currently, more than 50 organizations are involved.[16]

AI4AI's resources section provides templates, playbooks, and learning resources for national and sub-national governments to structure their digital agriculture initiative. It also presents impact stories on AI innovation and adoption in India.[17] Individuals and organizations are invited to join the forum and help shape a better, more sustainable future.

AI4AI's Saagu Baagu initiative (the name means "agricultural advancement" in Telugu) has significantly improved the livelihoods of 7,000 chili farmers in India's Telangana district by enhancing yields and incomes through advanced agritech and data management. Supported by the Bill & Melinda Gates Foundation and implemented by Digital Green, the project resulted in a 21% increase in chili yields, reduced pesticide and fertilizer use (by 9% and 5%, respectively), and increased product prices by 8%, effectively doubling farmers' incomes.[18] Encouraged by this success, Telangana's government plans to expand the project to impact 500,000 farmers across five crops and 10 districts, demonstrating AI's transformative potential.

To fully harness AI's potential in building climate-resilient agriculture, concerted efforts by multiple stakeholders are needed:

- Governments and the agritech industry must invest in AI R&D for agriculture. They should also drive and support technology adoption among farmers.
- AI and agriculture researchers must collaborate to devise and develop viable AI solutions tailored to diverse agricultural contexts.
- Research institutions and significant stakeholders should focus on interdisciplinary studies to address AI's socioeconomic and ethical implications in agriculture.
- Governments should promote and subsidize implementations to foster AI in agriculture to make it climate-resilient and eco-friendly.

Here are a few recommendations to address the challenges in adopting AI and other technologies in agriculture:

- **Promote education and training.** Educate farmers and stakeholders about AI technologies, including their benefits, risks, and limitations.
- **Develop open data platforms.** Encourage the creation of open data platforms that facilitate the sharing of agricultural data and AI models for collective learning and innovation.
- **Prioritize ethical AI.** Ensure AI technologies adhere to ethical guidelines, including respecting data privacy, fairness, and inclusivity.
- **Choose affordable alternatives.** To reduce the cost of cloud computing services, farmers should consider avoiding large providers like Google, Microsoft, and Amazon. For example, Flexisaf, an African tech company, found a solution to its problem (the high cost of Google's Workspace) in Zoho, an Indian company that offered similar products at a lower price.[19]

In a recent article, WEF used lessons from a real-world project in India to show how AI can transform agriculture.[20] The article recommends adopting a public-private partnership framework. Other WEF recommendations include central and state government support and incentives, including incubators, start-up funding, government-backed venture capital, tax holidays, and exemptions.

Agritechs must focus on effective distribution and adoption rights to address the high cost of mechanizing agriculture, a barrier to making small rural farms more efficient and profitable. VLEs play a crucial role in this process, and connecting VLEs with private capital is a pathway to social development and change.[21] Technology must also be localized to meet the specific needs of each region.

Late last year, WEF identified seven key innovations needed to transform food and agriculture:[22]

1. **Accurate, accessible weather forecasts.** With extreme weather threatening crops and challenging farmers' adaptability, accurate weather forecasts are essential. Farmers need to anticipate short- and long-term conditions to make strategic decisions about planting, irrigating, fertilizing, and harvesting. For example, accurate state-level forecasts of seasonal monsoon rainfall could help Indian farmers optimize sowing and planting times, potentially providing an estimated $3 billion in benefits over five years at a cost of around $5 million.[23]
2. **Microbial fertilizers.** These fertilizers use bacteria to enhance the absorption of essential nutrients by plants and soil, reducing the need for nitrogen fertilizers (a significant source of GHGs). GenAI could assist in developing new types of fertilizers.
3. **Reducing methane emissions from livestock.** Livestock accounts for roughly two-thirds of agriculture's GHGs, so implementing measures to reduce methane emissions is crucial.
4. **Rainwater harvesting.** Helping farmers and communities implement effective rainwater harvesting techniques can significantly improve water availability and management.
5. **Lowering costs of digital agriculture.** Making digital agriculture technologies more affordable can help farmers optimize irrigation, fertilizers, and pesticides.
6. **Encouraging alternative proteins.** Promoting the production of alternative proteins can reduce the demand for livestock, lowering GHGs.
7. **Providing insurance and social protection.** Insurance and social protections that enhance people's well-being by reducing poverty and vulnerability through policies and programs can help farmers recover from extreme weather events and build resilience.

CONCLUSION

AI presents unprecedented opportunities to build climate-resilient and sustainable agricultural practices. Integrating AI into agriculture systems can enhance productivity, preserve resources, and mitigate climate risks. However, realizing this vision requires collaborative action and ethical stewardship to ensure that AI benefits all stakeholders and contributes to a more sustainable future.

REFERENCES

[1] "Share of GDP from Agriculture." Our World in Data, 24 May 2024.

[2] "Global Population Is Growing." EU Competence Centre on Foresight, 21 December 2022.

[3] "Emirates Declaration on Sustainable Agriculture, Resilient Food Systems, and Climate Action." Council of the European Union, 16 November 2023.

[4] B.P., Sreekanta Guptha, et al. "Agriculture 4.0 — A Journey Towards Sustainable Farming." Infosys, 18 May 2022.

[5] "Pesticides." Cotton Today, accessed July 2024.

[6] "John Deere Launches See & Spray Ultimate Technology." John Deere, 7 March 2022.

[7] CropX website, 2024.

[8] The Descartes Labs Platform, accessed July 2024.

[9] Wang, Guan, Yu Sun, and Jianxin Wang. "Automatic Image-Based Plant Disease Severity Estimation Using Deep Learning." *Computational Intelligence and Neuroscience*, Vol. 2017, No. 1, January 2017.

[10] Bernier, Catherine. "Weeding Robots: Redefining Sustainability in Agriculture." HowToRobot, 17 July 2023.

[11] AgShift website, 2024.

[12] Goel, Arushi, and Sowmya Komaravolu. "How Is Agritech Helping to Optimize the Farming Sector?" World Economic Forum (WEF), 31 October 2023.

[13] Neo, Gim Huay, and K.T. Rama Rao. "How to Make Digital Transformation of Agriculture Work. Lessons from Telangana." WEF, 15 June 2023.

[14] "Artificial Intelligence for Agriculture Innovation." WEF, March 2021.

[15] Kundu, Shilpi, Edward A. Morgan, and James C.R. Smart. "Farmers Perspectives on Options for and Barriers to Implementing Climate Resilient Agriculture and Implications for Climate Adaptation Policy." *Environmental Science & Policy*, Vol. 151, January 2024.

[16] "AI for Agriculture Innovation (AI4AI)." WEF, accessed July 2024.

[17] "Impact Stories." WEF, accessed July 2024.

[18] M.S.V., Janakiram. "How Indian Farmers Are Using AI to Increase Crop Yield." *Forbes*, 1 February 2024.

[19] Dosunmu, Damilare, and Ananya Bhattacharya. "African Tech Companies Are Ditching Google for a Small Indian Competitor." Rest of World, 22 April 2024.

[20] Neo and Rao (see 13).

[21] Limaye, Pushkar, Devansh Pathak, and Sandeep K. Sinha. "How Rural Entrepreneurs Are Driving Agritech Adoption." WEF, 4 April 2023.

[22] Winters, Paul. "These Are the Seven Key Innovations Needed to Transform Food and Agriculture." WEF, 7 December 2023.

[23] Winters (see 22).

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DIGITALLY ENABLING VIABLE AGRI-FOOD SUPPLY CHAIN ECOSYSTEMS FOR CLIMATE CHANGE ADAPTATIONS

Authors

Kasuni Vidanagamachchi, Athula Ginige, and Dilupa Nakandala

Climate change, driven primarily by greenhouse gases (GHGs) such as carbon dioxide (CO2), presents a significant threat to global food security by causing extreme weather events like droughts, floods, and heat waves.[1] These events could negatively impact agri-food supply chains (ASCs) by disrupting food production, logistics, and consumption, which could threaten food security for people.

Changes in temperature and rainfall directly reduce the amount of food produced, affecting food availability. Larger-scale disruptions to transportation routes can cause delays and increase costs, leading to food shortages or significant price increases. The unpredictability of these events complicates planning for farmers, affecting planting and harvesting schedules and resulting in inefficiencies, losses, and food waste.

Disruptions to ASCs vary greatly by region, influenced by local conditions that impact production, logistics, and consumption. For example, Singapore's approach to food insecurity during the pandemic differed from Australia's or India's. Food security requires a consistent, ample flow of food into food systems to feed populations worldwide, so ASCs must be prepared to address future challenges at both regional and global levels.

How can we prepare for climate change impacts on ASCs? One of the most relevant sources is the COVID-19 pandemic response, which provides unique insights into managing widespread disruptions. By studying the effective adaptations observed during pandemic disruptions, we identify how supply chains can be reconfigurable and responsive to various production, logistics, and consumption challenges. This involves establishing strategies that help adapt to diverse conditions while mitigating CO2 emissions, ensuring viability in food supply chains amidst evolving climate uncertainties. Emphasizing the integration of digital innovations and sustainable practices, we present a compelling case for a proactive and flexible approach to securing food production and logistics for the future.

LESSONS LEARNED FROM THE PANDEMIC

The pandemic exposed significant vulnerabilities in ASCs, highlighting the need for resilience and adaptability. A supply chain with the ability to adapt and survive a long-term disruption is called a "viable supply chain."[2] In this case, "viability" goes beyond measuring a company's capability to recover from disruptions; it involves ensuring that both supply chains and their ecosystems can survive short- and long-term crises.[3]

> **HOW CAN WE PREPARE FOR CLIMATE CHANGE IMPACTS ON ASCs?**

Lessons learned from the pandemic response include strategies to mitigate the impact of climate change on agri-food systems.[4,5] The pandemic disrupted agri-food systems, but no one died of starvation, implying that the systems adapted enough to meet consumer demand for food. Figure 1 shows how consumers around the world secured their food needs during the pandemic and presents a framework for a variety of adaptations observed globally.[6]

The global context was captured through literature; the local context considered was Sri Lanka. Production (activities from cultivation to harvesting), logistics (collection from farmers, processing, storage, and transport to a location where consumers can access food), and consumption (purchasing from retailers, including last-mile deliveries and final consumption) adaptations emerged and gave consumers access to multiple channels, supported by governments and new/existing technology.

PRODUCTION ADAPTATIONS

Governments in Sri Lanka, the Philippines, and Fiji launched home-gardening campaigns to promote local food production and reduce dependence on external supply chains. Highly urbanized countries such as Singapore promoted vertical farming using hydroponics, aeroponics, and aquaponics, increasing food production in urban areas to reduce import dependence.[7] Digital platforms provided farming knowledge and created farming communities on social media. This empowered consumers to engage in farming activities, making them "prosumers" and helping them share knowledge.

LOGISTICS ADAPTATIONS

Food hubs and farmer's markets managed the aggregation, marketing, and distribution of local food products, ensuring continuity in the food supply and supporting local producers. Virtual food hubs connected local producers with consumers through online platforms offering door-to-door deliveries to expand market reach.

CONSUMER ADAPTATIONS

Consumers grew their own food and shared it with their communities, shifted purchasing to local farmer's markets, used digital tools to order online, and formed communities to share information on food availability and home gardening. Retailers expanded their online presence, offering click-and-collect services and last-mile deliveries to increase food availability.

TYPES OF AGRI-FOOD SUPPLY CHANNELS

Existing ASC channels can be categorized into four primary modes (M1 to M4 in dark purple circle of Figure 1). A channel refers to the specific route or pathway through which goods move from producer to consumer. This includes all steps, processes, and entities involved in the transfer and delivery of the product:

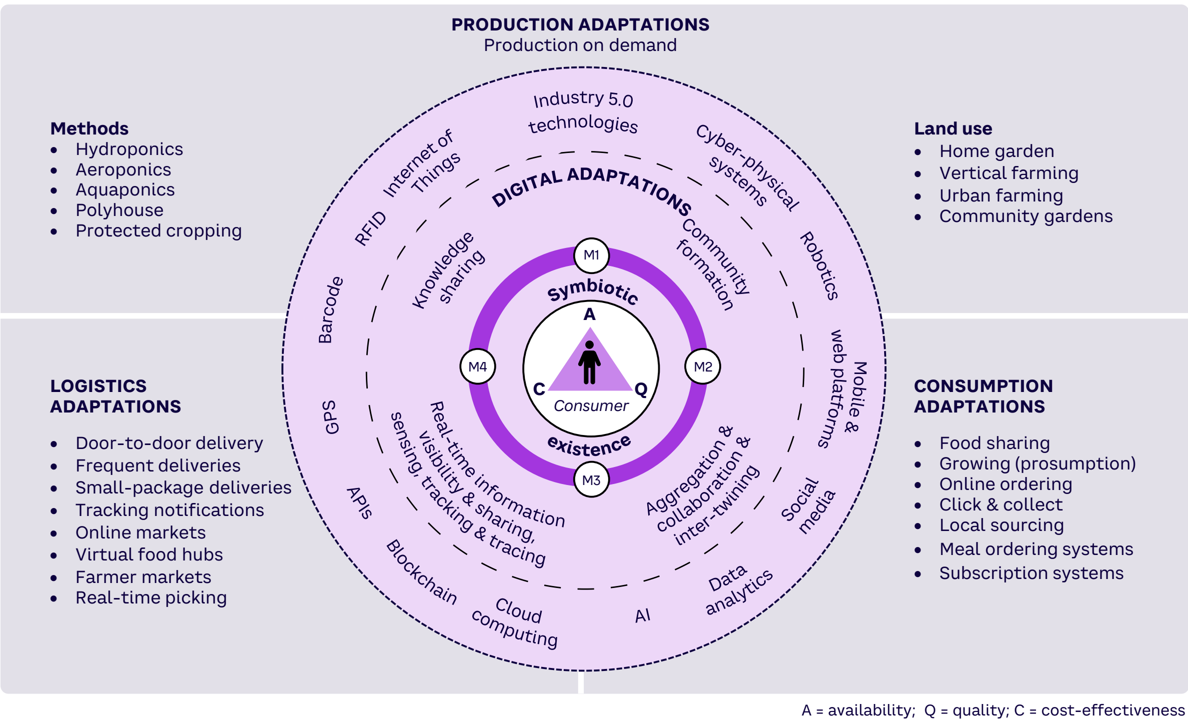


Figure 1. Viable ASC ecosystem framework

- **M1: Home gardening.** Consumers grow fresh agri-produce for self-consumption, acting as both producers and consumers (prosumers). This model emphasizes self-sufficiency and minimal reliance on external supply chains.
- **M2: Community-based sharing.** Consumers either individually or collectively grow fresh produce and share it within their community. This model fosters a sense of community and collective self-sufficiency.
- **M3: Farmer's markets and local shops.** Consumers buy fresh produce directly from local farmers. This model supports local economies and reduces the carbon footprint associated with long-distance transportation.
- **M4: Purchasing from retailers with intermediaries.** Consumers purchase fresh produce grown by distant farmers and handled by various intermediaries, such as wholesalers and supermarkets. This model offers convenience and variety.

Table 1 compares these four categories based on impact of climate change, resilience to disruptions, cost to consumers, access to variety, support for the local economy, quality and freshness of the produce, and community engagement.

DIGITAL ADAPTATIONS

Innovative technologies enable the above adaptations. When the logistics from conventional production locations to consumer demand locations were disrupted, the production locations changed, and logistics and consumption processes were reorganized accordingly. That provided visibility into smaller-scale production, logistics, and consumption methods.

CONSUMER-CENTEREDNESS

Digital technologies played a key role in enabling adaptations by diverting the information flow toward the consumer, empowering this group to make decisions. It allowed consumers to access these channels both physically and digitally, maximizing their desire for cost-effectiveness (C), quality (Q), and availability (A) of food, indicated by the middle triangle in Figure 1.[8]

SYMBIOTIC EXISTENCE

There is an interdependence among M1, M2, M3, and M4, in which the surplus from one channel can be used to support another, benefiting both parties.[9] This dynamic, interconnected ecosystem mirrors natural symbiotic relationships

PARAMETERS	HOME GARDEN (M1)	COMMUNITY-BASED SHARING (M2)	FARMER-CONSUMER DIRECT CONNECTION (M3)	RETAILERS WITH INTERMEDIARIES (M4)
Climate change impact	Low (no transportation)	Low (local sharing)	Moderate (local transportation)	High (long-distance transportation)
Resilience to disruptions	High (self-sufficient)	High (community support)	Moderate (local dependence)	Low (dependent on multiple intermediaries)
Cost to consumers	Low (self-grown; labor cost subject to one's time)	Low-to-moderate (shared resources)	Moderate (local market prices)	High (intermediary fees)
Access to variety	Limited (depends on what can be grown at home)	Moderate (community contributions)	Moderate (seasonal produce)	High (global sourcing)
Support for local economy	Neutral (individual effort)	High (community involvement)	High (local farmers)	Low (distant producers)
Quality & freshness	High (homegrown)	High (local produce)	High (local produce)	Moderate (long supply chain)
Community engagement	Low (individual activity, family member involvement)	High (community activity)	Moderate (market interaction)	Low (commercial transaction)

Table 1. Comparison of four ASC channels

and enables innovative business models (e.g., such as service-driven farming) to thrive in a post-industrial era. Thus, digital innovations blur traditional boundaries between production, logistics, and consumption, fostering a viable ASC.

CASE STUDY: SRI LANKA

Our study revealed that Sri Lanka's geographical diversity (variations in land availability, infrastructure, and population density across rural, urban, and semi-urban areas) has significantly shaped adaptations in the ASCs due to disruption to key activities in production, logistics, and consumption. These geographical factors influenced the ability of different regions to produce, distribute, and consume food during the pandemic (see Table 2).

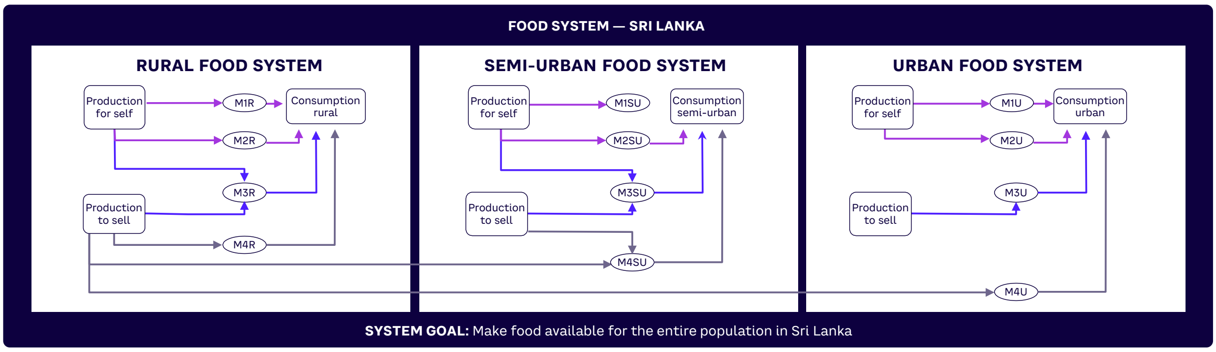
Figure 2 depicts the agri-food system in Sri Lanka. It shows agri-food flows from producers to consumers in different regions, subject to the key factors identified in Table 2. The overarching goal is to make food available for the entire population in Sri Lanka, regardless of regional divides. Figure 2 also shows the flows of food via M1 to M4 channels, where M1, M2, and M3 channels form short food supply chains (SFSCs), while M4 forms long food supply chains (LFSCs).[10,11] Below are the key insights gained.

RURAL RESILIENCE & SELF-SUFFICIENCY

Rural areas, abundant in agricultural land, produce significant agri-food that also supplies urban and semi-urban populations. Pandemic lockdowns disrupted this supply, causing food insecurity in urban areas while rural areas had a surplus. Adaptations in ASCs showed that traditional M3 and M4 channels became less accessible, leading to a rise in home gardening (M1). Although minimal before the pandemic, production-for-self (M1) grew significantly during the disruption, especially in rural and semi-urban areas, with some urban populations also starting gardens in their limited spaces. This shift increased resilience and self-sufficiency in rural areas.

FACTOR	RURAL	SEMI-URBAN	URBAN
Population density	Low	Moderate	High
Infrastructure, service levels	Low	Moderate	High
Land availability for food production	High	Moderate	Low/limited

Table 2. Key factors affecting adaptations in rural, semi-urban, and urban areas



SFSC	M1 — Home garden (grow & consume) M2 — Sharing (grow & share) M3 — Direct farmer to consumer selling (grow & sell) (use storage, transport, selling as a service)	**SFSC arrows**	M1,M2 flows M3 flows
LFSC	M4 — Supermarkets & shops with intermediaries (procure & sell)	**LFSC arrows**	M4 flows
Channels	(M1-M4)R — Channels available for rural consumers (M1-M4)SU — Channels available for semi-urban consumers (M1-M4)U — Channels available for urban consumers		

SFSC = short food supply chain; LFSC = long food supply chain

Figure 2. Flows of fresh agri-food within Sri Lanka

GOVERNMENT SUPPORT FOR HOME GARDENS

The government of Sri Lanka launched a program called "Saubhagya Gewatta" (which translates to "prosperous home garden") to create 1 million home gardens in the country. Due to land availability limitations, urban populations generally did not garden. Semi-urban populations practiced home gardening moderately, and most of the rural population had a home garden, making them more self-sufficient.

GOVERNMENT SUPPORT TO TRANSPORT FOOD

Although home gardening and local sharing increased, this couldn't meet demand in densely populated areas. The stricter lockdown rules in urban areas prevented food from rural areas from reaching urban markets, resulting in food shortages. With fresh food shortages, reliance on dry food grew. To address this, the government issued special permits to truck owners, enhancing the flow of food from rural to urban and semi-urban regions. Small trucks began door-to-door deliveries, and roadside sales became a common sight. Wholesalers from rural economic centers noted a shift during the pandemic: traditional urban vendors from urban areas were replaced by new players that obtained government permits to purchase and transport food.

The country also faced a fuel shortage, leading to forming queues at fuel stations. To help prevent food supply disruptions, the government issued special permits prioritizing fuel purchases for food transporters. This ensured an uninterrupted food supply across all regions, allowing the urban population to access fresh food and demonstrating the effectiveness of government intervention in maintaining food supply continuity.

SHARING KNOWLEDGE & CREATING COMMUNITIES TO ENSURE FOOD AVAILABILITY

Consumers in urban and semi-urban areas used digital tools to learn about gardening and share their experiences on social media. They also used these platforms to sell or share excess produce. During the pandemic and the subsequent economic crisis, use of the Govinena Home Garden mobile application increased significantly, highlighting its importance.[12]

RETAILERS ADOPTING ONLINE PLATFORMS TO MAKE FOOD MORE AVAILABLE

Urban areas with high population densities faced significant logistics disruptions, and online supermarkets became crucial in supplying fresh produce (M4U channels). Initially unable to meet demand, key supermarkets saw a surge in online orders as technology became more accessible. They adopted multiple methods, including phone calls and WhatsApp, to accept consumer orders.

Businesses with existing technology infrastructure for other industries developed e-commerce platforms and social media pages to sell fresh produce (repurposing) and expanded their portfolios (scalability). They developed innovative delivery methods by collaborating with other businesses (intertwining), including delivery services that previously specialized in perishables like meals and flowers (repurposing).[13]

Our case study shows that although supply chains were disrupted due to the pandemic, they quickly started reorganizing and creating new supply channels, making connections between food supply and demand subject to various local conditions. This was enabled by the government, businesses, communities, and digital technologies.

CREATING ASC ECOSYSTEMS

The metaphor of an iceberg is often used to describe situations where the visible part of an issue or phenomenon is a small portion of the whole (see Figure 3). In this situation, the tip of the iceberg represents the conventional, large-scale ASCs most people are familiar with, such as supermarkets, box stores, and large farmer's markets.

The larger part of the iceberg (submerged) represents the smaller channels that came about or became more prominent during the pandemic. These include local farmer's markets, community gardens, home gardens, food sharing, online channels, and door-to-door sales. These channels are less visible to the public but played a vital role in ensuring food security during the pandemic. They provided an alternative (and often more resilient) source of food, especially when larger supply chains were disrupted due to lockdowns, logistics failures, and labor shortages. They also have the advantage of promoting local economies, reducing food miles, and providing fresher food.

DIGITAL ENVIRONMENT FOR DYNAMICALLY ADAPTIVE ASCs

As shown in Figure 3, food supply methods can change based on varying conditions, allowing consumers to access multiple sources depending on their situation. When conditions change, certain methods move below the surface, and less popular methods come to the surface — provided diversity is present.

Diversity helps ASCs connect to changing conditions. That is why different regions of the country were subjected to different sets of conditions, and the adaptations happened differently. Figure 4 shows how supply chain structures can be dynamically reconfigurable in digital environments.[14] The components in green, purple, and blue represent production, logistics, and consumption, respectively. The overarching objective is to achieve food security, ensuring equitable access to sufficient, nutritious food at all times.

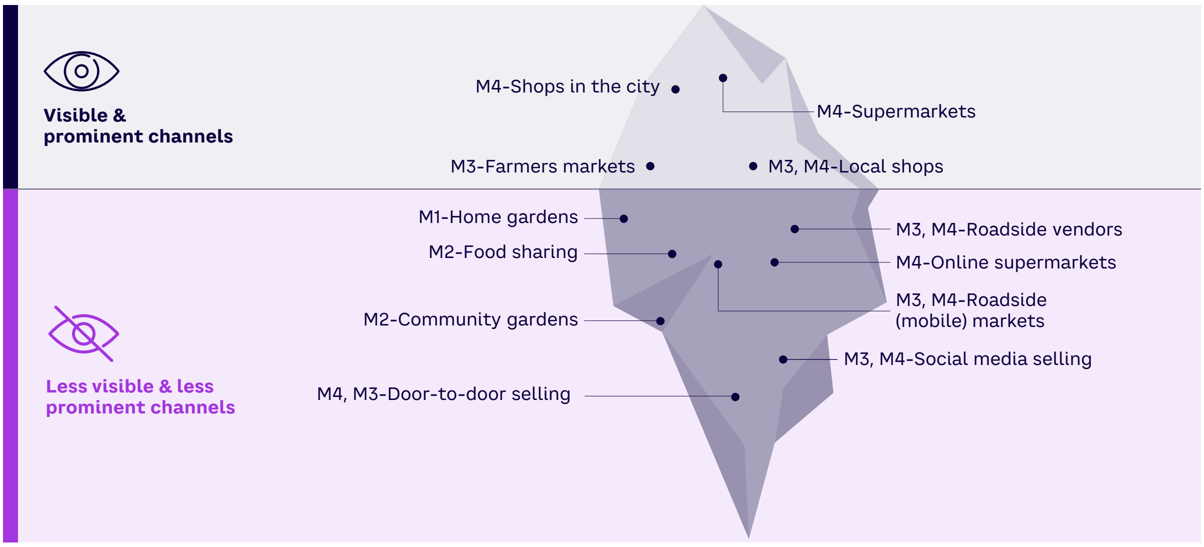


Figure 3. The iceberg of ASCs

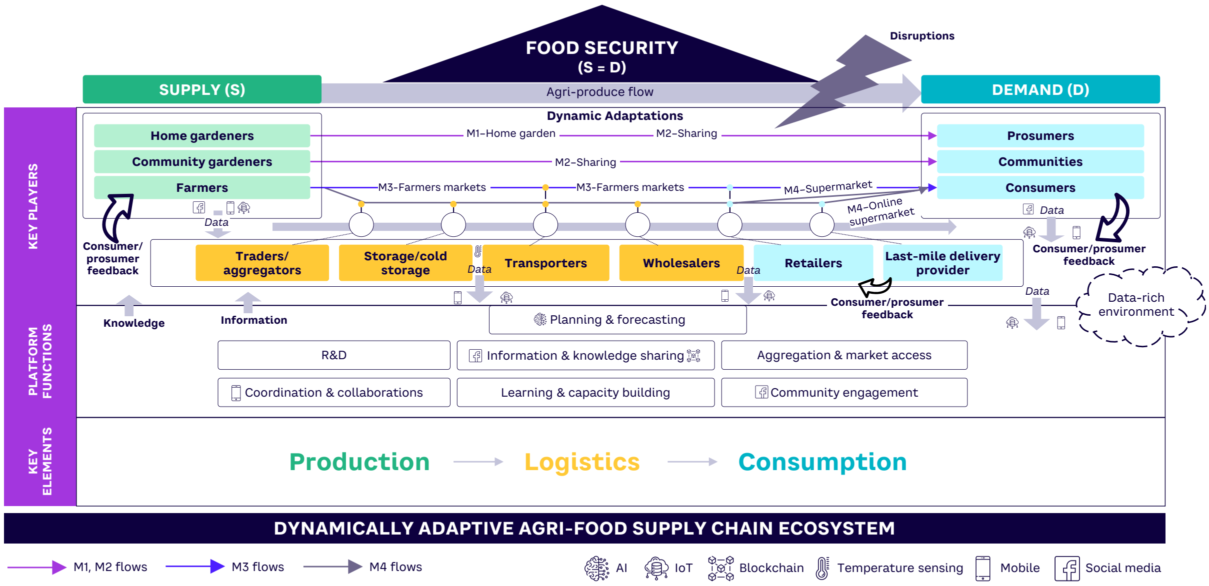


Figure 4. Blueprint for dynamically adaptive ASC ecosystem

Environmental disruptions can disrupt this equilibrium, making established supply chains vulnerable. The seamless connection between producers (farmers) and consumers is at the core of the supply chain's function, effectively aligning supply with demand. Additional components and entities (e.g., intermediaries, logistics service providers, technologies) are strategically organized to support this fundamental activity, optimizing each one's operational efficiency.

Digital interconnectivity among supply chain entities enables rapid reconfiguration. These technologies capture data across supply chains, creating a data-rich environment that facilitates the smooth movement of food from surplus areas to regions experiencing high demand. Simultaneously, consumers evolve into prosumers as they engage in both production and consumption.

Our research shows that consumers now have increased access to farming knowledge and market information, enhancing purchasing decisions and enabling active participation as prosumers through digital technologies. Social media and various knowledge platforms are the primary channels for disseminating this information.

This process necessitates the development of new business models responsive to changing conditions. Platforms that facilitate sharing and implementation of R&D are essential, as are robust systems for planning, forecasting, coordinating, aggregating, and collaborating.

Consumer feedback is crucial to this adaptive process, providing important insights into demand fluctuations, preferences, and satisfaction levels, enabling supply chain actors to adjust and optimize operations in real time. This iterative process ensures the ASC ecosystem remains responsive and resilient in dynamic environmental and market conditions.

CONCLUSION & RECOMMENDATIONS

Due to the unpredictable nature of climate change events, it's crucial to transition from short-term resilience to sustained survivability (viability) of supply chains and their ecosystems during prolonged crises. Key strategies include diversifying food supply methods with various channels and enabling digital interconnectivity. Local food supply chains, home gardening, and community gardens are essential for bolstering food security during crises, and farming practices such as vertical farming and hydroponics are vital for sustainable production on limited land. Innovative transportation and logistics methods are also essential.

Our study suggests a blueprint for dynamically adaptive ASC ecosystems within a digital framework. It involves reconfiguring production, logistics, and consumption methods based on local conditions to address diverse challenges while reducing CO_2 emissions. Integrating advanced technologies with sustainable practices and community engagement forms the foundation for a resilient, viable, and adaptive ASC ecosystem. Achieving these goals requires collaborative efforts from diverse stakeholders, including government bodies, businesses, farmers, technology providers, and local communities. This comprehensive approach secures long-term sustainability and efficiency in food production and distribution, ensuring food supply continuity amidst climate change and other global disruptions.

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REFERENCES

[1] Kogo, Benjamin Kipkemboi, Lalit Kumar, and Richard Koech. "Climate Change and Variability in Kenya: A Review of Impacts on Agriculture and Food Security." *Environment, Development and Sustainability*, Vol. 23, January 2020.

[2] Ivanov, Dmitry. "Viable Supply Chain Model: Integrating Agility, Resilience and Sustainability Perspectives — Lessons From and Thinking Beyond the COVID-19 Pandemic." *Annals of Operations Research*, Vol. 319, May 2020.

[3] Ivanov, Dmitry, et al. "Toward Supply Chain Viability Theory: From Lessons Learned Through COVID-19 Pandemic to Viable Ecosystems." *International Journal of Production Research*, Vol. 61, No. 8, March 2023.

[4] Ivanov et al. (see 3).

[5] Balezentis, Tomas, et al. "Measures for the Viable Agri-Food Supply Chains: A Multi-Criteria Approach." *Journal of Business Research*, Vol. 155, Part A, January 2023.

[6] Vidanagamachchi, Kasuni, and Athula Ginige. "Consumer-Centred Viable Agri-Food Supply Chain Ecosystem and Potential Digital Enhancements: An Exploratory Study." *Proceedings of the Australasian Conference on Information Systems (ACIS) 2023*. Association for Information Systems (AIS), December 2023.

[7] Naskali, A. Teoman, Ozgun Pinarer, and A. Cagri Tolga. "Vertical Farming: Under Climate Change Effect." In *Environment and Climate-Smart Food Production*, edited by Charis M. Galanakis. Springer, 2022.

[8] Vidanagamachchi and Ginige (see 6).

[9] Vidanagamachchi and Ginige (see 6).

[10] SFSCs are systems in which the production and consumption of food are closely linked in terms of geography, social context, and economy. They aim to minimize the distance and number of intermediaries between producers and consumers. Benefits include supporting local economies, enhancing transparency, improving food quality, and potentially reducing environmental impacts; see: Marsden, Terry, Jo Banks, and Gillian Bristow. "Food Supply Chain Approaches: Exploring Their Role in Rural Development." *Sociologia Ruralis*, Vol. 40, No. 4, December 2002.

[11] LFSCs involve multiple intermediaries and cover extensive geographic distances. They feature complex logistics, including multiple stages (e.g., processing, packaging, warehousing, and transportation), often across regions or countries. This complexity can affect traceability and have an environmental impact due to extended transportation; see: Ilbery, Brian, and Damian Maye. "Food Supply Chains and Sustainability: Evidence from Specialist Food Producers in the Scottish/English Borders." *Land Use Policy*, Vol. 22, No. 4, October 2005.

[12] Vidanagamachchi and Ginige (see 6).

[13] Intertwining, substitution, scalability, and repurposing are the four generalized adaptation strategies for viable supply chains; see: Ivanov, Dmitry. "Supply Chain Viability and the COVID-19 Pandemic: A Conceptual and Formal Generalisation of Four Major Adaptation Strategies." *International Journal of Production Research*, Vol. 59, No. 12, March 2021.

[14] Vidanagamachchi and Ginige (see 6).

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