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BRIDGING KNOWLEDGE AND RESILIENCE: COMMUNICATION AND EXTENSION STRATEGIES DRIVING AGRICULTURAL INNOVATION IN THE UNITED STATES

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ABSTRACT----------
The revolution of the United States agriculture amid increasing climatic, technological and socioeconomic change has elevated the importance of effective communication and extension systems as central method in sustaining innovation and resilience. Traditional top-down dissemination models rooted in early models of Land-Grant and Cooperative Extension systems are becoming less sufficient in addressing the complexity of contemporary farming systems. This narrative review synthesizes recent evidence (2020-2025) on the emergence of digital innovation-, participatory learning-, and resilience-based communication and extension strategies in the U.S. Drawing on interdisciplinary scholarship and policy frameworks, including federal extension modernization and climate-related initiatives, the review recognizes four convergent trends: the digitalization of agricultural knowledge, the revitalization of participatory and co-learning methods, the integration of communication in resilience frameworks, and the development of hybrid, policy-aligned communication ecosystems. Collectively, these developments shift from linear information transfer toward a more adaptive and networked system of knowledge co-production. Despite significant progress, persistent issues remain such as digital inequities, institutional fragmentation, limited evaluation of resilience outcomes, and unresolved ethical concerns related to data. This review concludes that communication and extension should be conceptualized as underlying infrastructures of agricultural resilience, connecting research, policy, and practice through dynamic, inclusive, and evidence-based interaction. Advancing U.S. agriculture requires a more participatory and flexible environment that integrates emerging technologies with collaborative decision-making.

KEYWORDS: *Agricultural Innovation · Communication Strategies · Extension Systems · Climate Resilience · Digital Agriculture* ----------

INTRODUCTION

In the United States, agriculture constitutes the foundation of national food security, rural livelihoods, and economic stability. The agricultural and food sector contributes approximately 5.4% of the nation's gross domestic product and supports the livelihoods of more than 20 million individuals through direct and indirect employment within the food system (USDA, 2024). Yet, behind this economic productivity lies an industry increasingly strained by accelerating climate change, soil degradation, market volatility, and demographic shifts in the rural labor force. These intersecting challenges underscore the need not only for continued scientific and technological innovation but also for robust systems of knowledge exchange and capacity building that effectively translate research into practice and align emerging innovations with the lived realities of farmers.

The Land-Grant University System and the Cooperative Extension Service (CES) established under the Smith-Lever Act of 1914 form the foundation of agricultural extension in the United States for over a century (Franz & Townson, 2021). This network has historically served as the connective tissue between scientific discovery and on-farm implementation, supporting the diffusion of innovation and adaptive management across diverse agricultural systems. However, the environment of knowledge production and sharing has altered significantly in the twenty-first century. Farmers now operate a data-driven economy where management decisions are informed by digital technologies,

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artificial intelligence, and remote sensing rather than soil or rainfall patterns (Klerkx & Rose, 2020; USDA, 2024). Concurrently, the information demands of farmers have become more complex, shaped by new regulations, sustainability requirements, and consumer expectations in terms of traceability, environmental responsibility, and climate-intelligent production (Bronson & Knezevic, 2021).

Although the U.S. remains a global leader in agricultural research and technological innovation, including the invention of hybrid seed, biotechnology, and precision agriculture, the current challenge is not how to produce the knowledge but rather how to translate and equitably apply the knowledge across the various agricultural contexts. Through the use of extension and communication systems, diffusion of innovation is expected to not only benefit large-scale agribusinesses but small and mid-sized family farms, especially in addressing inequalities in technological access, digital literacy, and adaptive capacity (Lamm et al., 2023; Rogers et al., 2022). Despite significant investment in extension infrastructure, many farmers, especially in resource-constrained or marginalized areas, have limited location-specific information to respond effectively to drought, pest outbreaks, and market shocks in a timely manner (Miller et al., 2021).

The increasing nature of the digital divide, which is characterized by the differences in broadband connections, data infrastructure and access to new technologies, further widens the disparity in the adoption of innovation and resilience-building (Whitacre & Gallardo, 2022). Recent studies indicate that many rural Americans lack reliable access to internet, limiting participation in digital learning networks, precision agriculture tools, and real-time advisory systems (FCC, 2023). These challenges reveal structural constraints within extension systems where the lack of integration and cooperation of extension systems across federal, state, and local levels hinders coordination, collaboration, and consistency in communication strategies (Lamm et al., 2023; Franz & Townson, 2021).

These excerpts reflect the broader question that guided this review: How do U.S. agricultural communication and extension systems integrate digital innovation, participatory learning and institutional collaboration to support sustainable agricultural innovation and resilience? Addressing this question is not only crucial for advancing agricultural sustainability but also for achieving more national policy goals related to climate adaptation, rural revitalization, and equal economic development.

Communication and extension are also listed as critically important in the transition to a low-carbon and resilient agricultural system in the Climate-Smart Agriculture and Forestry (CSAF) framework by the United States Department of Agriculture (USDA, 2023). The USDA continues to support climate adaptation, sustainable production, and knowledge exchange through ongoing programs within its conservation, research, and rural development portfolios, even though parts of the CSAF initiative have undergone administrative review and partial restructuring under the current administration (USDA, 2023). However, to achieve this potential, it is essential to reexamine how knowledge is produced, validated, and shared between scientists, extension professionals, private-sector actors, and farmers themselves. This intervention extends beyond enhancing the flow of information to developing learning-oriented and networked systems that support knowledge co-production, trust-building, and adaptive capacity across agricultural communities.

U.S. agricultural and extension systems are at the intersection of this changing environment. The traditional linear models of technology transfer, which were once proven successful in disseminating innovations such as improved crop varieties or soil management techniques, according to Franz & Townson (2021) and Rivera & Qamar (2020), are now inadequate in addressing complex and interdependent challenges related to sustainability. Emerging communication strategies should integrate digital technologies, participatory approaches, and resilience-oriented models into comprehensive systems capable of responding dynamically to evolutions. This review thus examines the evolution of communication and extension strategies in the U.S. toward more adaptive, inclusive and technology-enabled systems that not only accelerate innovation but also enhance the resilience of farmers and the agricultural sector as a whole.

Emerging Trends and Thematic Analysis.

Contemporary U.S. agricultural communication and extension systems show substantial changes driven by technology advancement, policy reform, and increasing social change. The field has developed between 2020 and 2025 to be less traditional and top-down and more digitally networked, participatory systems that are focused on innovation, resilience, and equity. Recent literature, including peer-reviewed papers, institutional and policy documents, and empirical studies, was synthesized thematically and shows four significant and interconnected trends:

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(1) the digitalization of agricultural knowledge systems;
(2) the emergence of participatory and co-learning approaches;
(3) the integration of communication into resilience frameworks; and
(4) the development of hybrid, policy-aligned communication ecosystems.
Together, these themes demonstrate both the progress and current gaps in the conceptualization and practice of agricultural communication and extension in the U.S.

Digitalization of Agricultural Knowledge Systems

The most prominent trend reshaping U.S. agricultural extension is digital transformation. Over the past five years, artificial intelligence (AI), remote sensing, mobile applications, and cloud-based analytics technologies have transformed how agricultural knowledge is generated, accessed and shared among farmers and agricultural stakeholder. Klerkx and Rose (2020) argue that digitalization is more than a technology boost but a restructuring of data-driven governance within agricultural knowledge systems. Federal programs in the U.S, such as the USDA Climate Hubs, the Extension Modernization Agenda of the National Institute of Food and Agriculture(NIFA), and the Precision Agriculture Connectivity Act (2018), are leading this transition with the overall goal of expanding broadband infrastructure, integrating data systems, and enhancing digital literacy among producers (NIFA, 2022; U.S. Congress, 2018).

Empirical studies highlight the possibilities of digital tools to extend the reach of communication and analytical capacity of extension programs. For example, Prokopy et al. (2022) discovered that the use of digital extension platforms enhanced the adoption of climate adaptation practices among corn and soybean growers in the Midwest by enabling real-time decision-making. Similarly, Lamm et al. (2023) reported increased dependence of U.S. extension professionals on social media, webinars, and decision-support dashboards to deliver timely research-based information. These digital modalities proved crucial, particularly during the COVID-19 pandemic, when face-to-face interaction was extremely difficult.

Despite these improvements, the benefits of digitalization remain unevenly distributed. Small-scale, remote, and resource-constrained farmers remain on the periphery of the digital divide due to constraints in broadband infrastructure, device availability, and digital literacy (Whitacre & Gallardo, 2022). According to the Federal Communications Commission (FCC, 2023), approximately 22% of rural counties in the U.S. still lack access to high-speed internet, limiting participation in digital extension networks. Moreover, digital tools have the potential to widen inequalities by favoring data-rich commercial farms over those with limited resources. Bronson and Knezevic (2021) caution that in a process, there is a danger of establishing informational asymmetries when ownership of corporate data and proprietary algorithms erodes transparency and local agency.

Nonetheless, the trend of digitalization has transformative potential in combination with participatory design principles (Klerkx & Rose, 2020). New hybrid models such as digital field schools, interactive climate dashboards, and farmer-owned data cooperatives show how technology can enhance rather than undermine producer agency (Bronson & Knezevic, 2021; Prokopy et al., 2022). One illustrative example is the USDA-supported digital platform called the OpenTEAM Initiative, which allows farmers to co-own, manage, and contribute data for climate-resilient decisions. These efforts imply that the future of digital extension should focus on both infrastructure investment and data sovereignty as a way of making sure that communications are a two-way process that is based on trust, usability, and shared governance (Bronson & Knezevic, 2021).

Emergence of Participatory and Co-learning Approaches

Alongside digital transformation, participatory and co-learning models have re-emerged as central to effective agricultural communication and extension in the U.S. These strategies position farmers as the driving force of innovation and knowledge creation, and not the passive audience of expert information. Within this paradigm, the Cooperative Extension Service (CES), which was traditionally the channel of technical guidance, is increasingly redesigned into a facilitator of social learning, peer exchange, and collective experimentation (Franz & Townson, 2021).

Empirical studies confirms that participatory models improve innovation adoption as well as resilience. For example, Knook et al. (2024) showed participatory extension programs in New Zealand enhanced farmers adaptive capacity through peer learning and localized experimentation. While this study originated outside of the U.S., their findings have influenced U.S. initiatives such as the Extension Foundation's eFieldbook and on-farm research networks

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operated by land-grant universities. the Similarly, Odongo et al. (2023) emphasized the contribution of pluralistic extension systems to empower the network of farmers and governance. The pluralistic model of the competition of public, private, and civil-society actors reflects the contemporary U.S. agricultural landscape, where federal agencies, agritech corporations, non-governmental organizations, and producer network together define the direction of innovation (Odongo et al., 2023; Rivera & Qamar, 2020).

Despite these developments, participatory communication in the U.S. remains institutionally uneven. Most extension programs still have hierarchical designs that give precedence to the expert versions of dissemination rather than co-production. The processes of funding tend to incentivize short-term adoption indicators over long-term learning outcomes, reinforcing transactional rather than transformational engagement (Lamm et al., 2023). Furthermore, the facilities of time, sources, and training in facilitative communication are the limitations of extension professionals, which restrict their capacity to maintain participatory processes (Monroe et al., 2021). These challenges necessitate the need to invest in capacity building and policy changes that incorporate participatory principles through the program evaluation systems.

The participatory turn raises new ethical and epistemological questions. Who determines what knowledge is relevant? How do scientific, experiential, and Indigenous knowledge systems interact within collaborative spaces? Bergez et al. (2023) argue that epistemic diversity is a crucial source of resilience, but communicative structures that promote dialogue across knowledge cultures are needed to facilitate this diversity. In the U.S. context, this implies developing extension programs that respect the tradition of local knowledge while integrating it with cutting-edge scientific insights to create adaptive systems that are technologically advanced and socially grounded (Darnhofer, 2021; Franz & Townson, 2021).

Integrating Communication into Resilience Frameworks

Integration of communication into resilience theory is one of the significant conceptual shifts in recent literature. Resilience, which was formerly considered as an ecological or economic property, is increasingly understood as a communicative process grounded in networks of information exchange, trust, and shared meaning (Darnhofer, 2021). Withing this perspective, communication is not just a channel of transmitting adaptation strategies; it is a medium in which resilience is learned, practiced, and institutionalized.

An example of this perspective in the context of American agriculture is the United States Department of Agriculture's inclusion of information and knowledge exchange in the Climate-Smart Agriculture and Forestry (CSAF) paradigm (USDA, 2023), which is one of the pillars of resilience-building. This connection is supported by empirical studies. Prokopy et al. (2022) found that communication frequency and network trust were important predictors of farmers' adaptive management behavior under climate stress. Similarly, Lemos et al. (2021) revealed that resilience in agricultural systems is a result of the claimed knowledge-action systems in which science, policy, and practice interplay in the form of communication.

Making communication a core component of resilience transforms extension from a model of information transfer to one of adaptive governance. It also requires measures of the relational and cognitive aspects of resilience, including social capital, collaborative problem-solving, and institutional learning (Darnhofer, 2021; Lemos et al., 2021; Meuwissen et al., 2019). However, the success of most U.S. extension programs is measured based on standard performance indicators such as participation levels or adoption rates, which do not provide sufficient information on the outcomes of resilience (Lamm et al., 2023). To address this gap, new models that offer multidimensional evaluation tools can be applied to U.S. extension systems, including the Resilience Wheel developed by Knook et al. (2024) and the Community Capitals Framework Flora and Flora, 2019). These frameworks directly connect communication to resilience capacity, which provides a channel for evidence-based extension programs.

Hybrid and Policy-Aligned Communication Ecosystems

The most promising development of agricultural communication and extension systems in the United States is the convergence of the digital and participatory paradigms, which remains a novel development at present. Human-centered models with technology efficiency-hybrid models are emerging in recent initiatives (Franz & Townson, 2021). Examples include the USDA Climate Hubs (USDA, 2023), which combine remote sensing data with local knowledge networks to generate adaptation advice specific to the region-specific adaptation guidance (Prokopy et al., 2022). Similarly, the land-grant university Extension system is increasingly using mixed digital-in-person modalities via online learning platforms to supplement on-farm demonstrations and peer interactions.

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At the policy level, this integration aligns with larger national objectives related to climate adaptation, equity, and innovation. The recent Farm Bill highlights data sharing, inter-agency coordination, and inclusive outreach as the central needs of extension modernization (U.S. Congress, 2023). However, translating these mandates into operationalized communication systems remains difficult. Institutional fragmentation persists across agencies, and the diffusion of innovation between states is significantly different. According to Lamm et al. (2023), not all state extension services possess the digital infrastructure and the workforce necessary to fully implement hybrid models. To eliminate these gaps, there is a need for a long-term investment in digital literacy, cross-sector collaborations, and policy coherence.

Hybrid ecosystems also raise unresolved questions related to governance, data ethics, and power dynamics. Who owns the data gathered during the interactions between farmers and extension agents? What steps may be taken to protect privacy while promoting open innovation? Bronson and Knezevic (2021) argue that without transparency in the governance systems, digital participatory programs risk replicating existing inequity. These issues are addressed by what Klerkx and Rose (2020) refer to as responsible digitalization, a commitment to inclusive, reflexive, and democratically accountability in the design of technologies and policies.

Conceptual Integration: A Framework for Communicative Resilience

The four themes synthesized in this review converge in the concept of Communicative Resilience (Figure 1), where agricultural innovation is positioned at the intersection of digital innovation, participatory learning, and institutional governance. In this model, digital tools expand informational reach, participatory structures ensure local relevance and legitimacy, and governance structures offer stability and coordination. With the combination of these components, resilience emerges through adaptive feedback loops, enabling the U.S. agricultural extension systems to continuously learn and evolve.

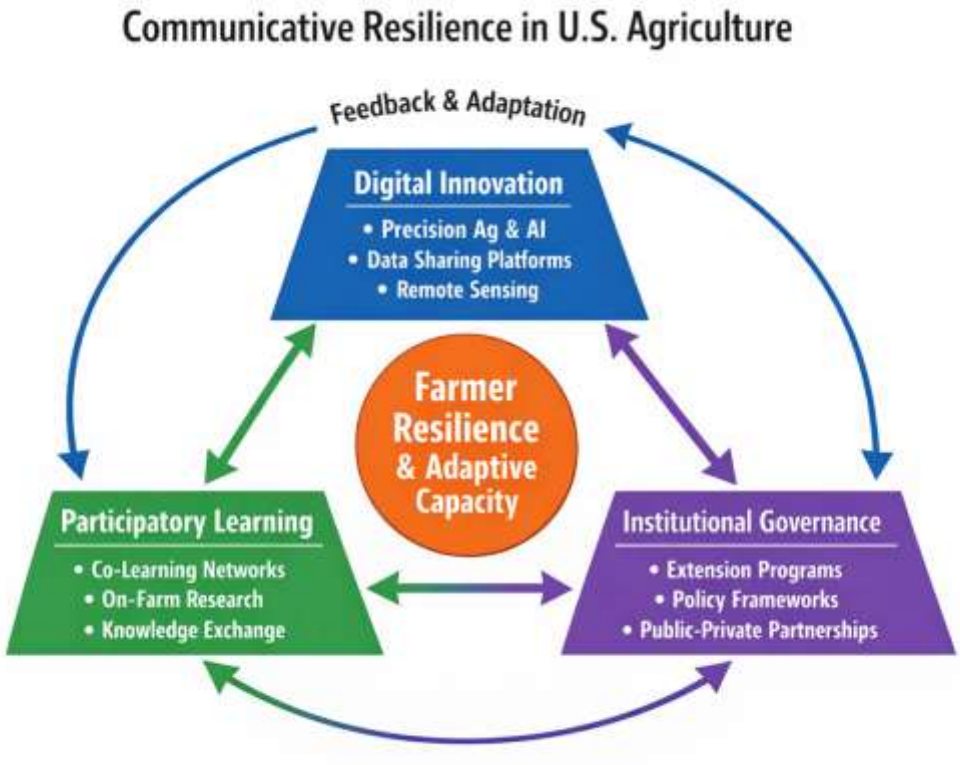

Figure 1: Conceptual model of Communicative Resilience in U.S. agriculture

The intersection of digitalization, participatory engagement, and resilience thinking provides a guide on how to make extension an active learning ecosystem. This potential, however, will only be achieved through a concerted effort in the fields of research, policy, and practice to ensure that communication is not only a source of innovation, but of a more equitable and resilient agricultural future. The conceptual model of communicative resilience highlights both

the potential and the limitations of current approaches, underscoring the need for intentional integration across technological, social, and institutional dimensions.

CONCLUSION

The transformation in U.S. agricultural communication and extension demonstrates a larger paradigm shift towards adaptive, participatory, and technologically-based knowledge systems. This narrative review identifies four overlapping trends shaping extension evolution: digitalization, participatory co-learning, resilience integration, and hybrid policy-aligned communication ecosystems. Collectively, these developments transform communication into drivers of innovation and resilience, rather than a passive channel of information.

Despite significant progress, persistent issues remain, including digital inequities, disjointed government structure, limited evaluation of resilience outcomes, and unresolved ethical questions surrounding data utilization. The interdisciplinary study and coordinated policy to tackle these gaps will need to align communication infrastructures with national objectives of climate adaptation, food security, and rural development.

For researchers, this review underscores the need to develop integrative frameworks that bridge communication theory, systems thinking, and resilience science. For policymakers, investments in broadband infrastructure, professional capacity building, and ethical data governance are vital. By converging digital innovation with participatory interaction, the U.S. can advance toward an equitable, knowledge-based, and resilient agricultural future in which communication serves as both the bedrock and the driver of sustainable change.

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