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From fragmented innovation to agricultural system transformation

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1 Agriculture has entered a new era of system challenges

For much of modern agricultural history, its central objective has been to increase production. Advances in genetics, crop and animal management, fertilizers, irrigation, pest and disease control, mechanization, and food processing have delivered substantial gains in food supply. That objective remains essential but it is no longer sufficient. Agricultural systems must now secure food supplies sustainably while using resources more efficiently, reducing environmental impacts, protecting animal and human health, remaining resilient to climatic and market shocks, and sustaining viable livelihoods.

These outcomes are tightly interconnected. Measures that increase yields can also increase demand for water, fertilizer or other inputs, or change the vulnerability of the system to climatic risks. Although more efficient livestock production must reduce resource use per unit of output, expanding production can also increase total feed demand and concentrate manure. Stricter food safety or quality standards can improve public health but raise compliance costs and create barriers for smaller producers. Digital recommendations might be technically sound but difficult to implement where data, finance, connectivity, skills or institutional support are limited. Similarly, policies that accelerate the adoption of new practices can redistribute costs and benefits between farmers, consumers and society.

Agriculture should therefore be understood as a connected agrifood system rather than a collection of separate production problems. Natural resources, crop and animal production, food processing, markets, consumption, digital infrastructure, and public institutions interact through flows of materials, information and value. The central challenge is no longer simply a shortage of innovation within individual fields. Rather, it is the difficulty of aligning innovations across the system, managing trade-offs and unintended consequences, and directing collective action towards shared outcomes.

2 Why fragmented innovation is no longer sufficient

Agricultural research has advanced through specialization. This structure has produced deep knowledge and effective technologies, and it will remain indispensable. The problem arises when improvement within a single discipline, stage or performance indicator is treated as evidence of improvement in the system as a whole.

2.1 Fragmented knowledge and criteria of technology performance

Disciplines often define success using indicators that align with their own analytical boundaries. Crop research might emphasize yield, animal science might focus on feed

conversion or animal health, food science might assess safety and composition, artificial intelligence might report predictive accuracy, and policy research might examine adoption or compliance. Each measure would be meaningful within its respective domain but none captures the full consequences of an intervention.

A higher-yielding crop can increase pressure on the supply of water, nutrients or other inputs. A feeding strategy can improve animal performance while shifting land-use pressure to regions that produce feed. A food safety or quality standard can benefit consumers while imposing costs that cannot be fully recovered through market prices. An empirical model might predict field conditions accurately but fail to influence decisions because the required data are unavailable, the recommendation is impractical or it conflicts with farmer incentives. Disciplinary excellence therefore does not necessarily translate into system improvement. The relevant unit of evaluation is the set of consequences generated across production, environmental quality, health, markets and livelihoods.

2.2 Fragmented system boundaries

Agricultural studies also differ in their analytical boundaries, which can range from the plant or field level to the herd, farm, processing facility or retail market. While such boundaries are necessary for tractable analysis, they risk producing misleading conclusions when local results are extrapolated to infer system-wide gains.

Reducing mineral fertilizer use on a farm, for example, does not necessarily reduce nutrient losses across the broader agrifood system. The net effect depends on a complex interplay between yield responses, manure management, feed imports, crop allocation, food waste and nutrient recovery. Similarly, lowering the environmental footprint of livestock production in one region might increase reliance on feed or animal products produced elsewhere. Further along the late food supply chain, extending food shelf life can reduce waste but require additional energy, packaging and processing. Narrow analytical boundaries can therefore lead to the misinterpretation of shifting of environmental or economic burdens for genuine system improvement.

A systems perspective that extends from natural resources through production, processing, distribution and consumption to recovery and recycling is therefore essential for the development of sustainable agriculture. Such a perspective must also account for social and economic conditions, including technical standards, market prices, institutional structures, information exchange and public regulations. This does not require every study to model every component. It does, however, require researchers to identify the interactions excluded from their analysis and assess whether those exclusions could materially alter, or even reverse their conclusions.

2.3 Fragmented innovation objectives and processes

Agricultural research and policy initiatives frequently optimize one outcome at a time, such as yield, emissions, food quality, model performance or technology uptake. However, sustainable transformation requires the joint consideration of several outcomes and how their costs and benefits are distributed. The relevant question is therefore not simply which technology performs best in isolation but which combination of technologies, institutions and practices delivers the strongest overall outcome, for whom, at what cost, and over what time horizon.

Fragmentation also extends across the stages of innovation through which innovation moves from knowledge generation to implementation and impact. Scientific discovery, technology development, service provision, market formation and policy design often evolve independently with limited coordination between them. As a result the technologies developed by researchers might not align with the realities of farm production. Producers might bear the cost of environmental improvement while downstream firms or society capture most of the benefit. Food quality could improve without credible certification or sufficient market recognition. Similarly, policy targets might be announced without the operational tools, incentives or delivery capacity needed to achieve them. When farmer and consumer experiences feedback into these processes only after the research agenda and implementation model have already been established, opportunities for learning and adaptation are lost.

Fragmentation, therefore, cuts across knowledge domains, system components, objectives, actors and stages of innovation itself. It is not simply a matter of disconnected activities but rather one of weak linkages between the elements that

collectively determine whether an innovation can generate system-level outcomes. Addressing this challenge therefore requires a shift in the unit of innovation, from the development of isolated technologies or interventions towards the configuration, coordination and overall performance of the agricultural system.

3 An integrated framework for agricultural system innovation

Agricultural system innovation is the coordinated redesign of knowledge, technologies, production processes, value chains and governance arrangements to improve the performance of the agrifood system as a whole. It emphasizes redesign, interaction and system-level outcomes.

Redesign means changing the structure and operating rules of the system where necessary, rather than simply adding new technologies to an unchanged production model. Interaction means treating biological, environmental, technical, economic and institutional conditions as interconnected components of the causal system. System-level evaluation means tracing where costs and benefits arise, which groups receive them, and how effects develop and are redistributed over time.

3.1 Complementary capabilities and cross-domain interfaces

Six complementary capabilities are central to agricultural system innovation. Agronomy and environmental sciences provide the basis for managing crops, soils, water, nutrients, biodiversity and ecosystem processes. Animal science and veterinary medicine address animal productivity, nutrition, disease, welfare, biosecurity and crop-livestock integration. Food science and health define the safety, nutritional, quality and health attributes that the food system should deliver. Artificial intelligence and digital technologies support data integration, diagnosis, prediction, traceability and decision-making. Economics, markets and social sciences explain how prices, incentives, preferences, behavior, market structures and distributional effects shape decisions across the agrifood system. Agricultural policy and governance establish public goals, standards, regulatory frameworks, rights and mechanisms for coordinating actors with different interests.

These capabilities are complementary rather than parallel. The most consequential questions often arise at their interfaces, and across sectors and disciplines: how soil and crop management affect food quantity, quality and environmental performance; how animal health, feed use, manure management and environmental impacts interact; how dietary patterns and consumer preferences reshape land use, crop and livestock production and food processing; how prices, incentives and market structures influence producer adoption and consumer responses to new product attributes; how digital technologies affect information flows and decision-making under different conditions of access, skills and institutional support; and how standards and governance arrangements shape value-chain competitiveness, inclusion, and the distribution of costs and benefits.

Designing a coherent strategy to expand the supply of healthy food while reducing its environmental footprint requires interdisciplinary innovation and cross-sectoral coordination. On the demand side, health objectives should first be translated into measurable and verifiable product attributes. On the supply side, agronomy and animal science can identify feasible food production practices for achieving those attributes. Environmental analysis is then needed to determine whether impacts decline across the relevant system boundary. Economic and market analysis is needed to assess how prices, incentives, consumer preferences and market structures influence producer and consumer responses, and how the associated costs and benefits are distributed. Markets and certification systems should communicate verified attributes to buyers, while artificial intelligence-enabled digital technologies can strengthen monitoring and traceability. Policy design must also address cost allocation, performance verification and safeguards against excluding smaller producers that lack capital, infrastructure or technical support. No single discipline can determine the final system design.

Cross-domain integration does not require researchers to become generalists. It requires explicit interfaces, shared outcome measures and research designs that make interactions, spillovers and trade-offs visible.

3.2 Whole-chain and multiscale integration

Agricultural systems have often been designed primarily around production, with markets expected to absorb whatever output is generated. This approach is increasingly inadequate. Production must respond more directly to societal needs for

nutrition, safety, quality, affordability and environmental performance.

Consumers are therefore more than the final recipients of food. Their preferences, purchasing decisions and political demands influence standards, prices and production choices. These influences are mediated by processors, retailers, certification bodies, public procurement and regulation. A broad preference for healthier or environmentally sustainable food will not necessarily alter production unless it is translated into verifiable attributes and economic returns that justify the required changes.

Whole-chain integration also requires attention to material and value flows. Crop residues, manure, processing byproducts and food waste could become resources but recycling is not automatically beneficial. Its value depends on nutrient content, contamination risks, transport distance, treatment requirements and regional production structures. The objective is not to close every loop locally but rather to organize production, processing, consumption and recovery across appropriate regional and global scales so that total resource use and environmental burdens are reduced across the system.

The appropriate scale of intervention depends on the nature of the problem being addressed. Soil-crop system management could be most effective at field level, whereas crop-livestock integration often requires coordination across farms or regions. Similarly, watershed pollution needs to be managed according to ecological rather than administrative boundaries, while food standards and dietary policies would most likely require national action, and trade-related effects might extend across borders. Interventions that appear efficient at one scale can nevertheless generate spillovers, leakage, or shift costs and benefits at another scale. A multiscale perspective is therefore essential for identifying where coordination is needed, how impacts are distributed across scales, and where the cost of intervention could ultimately be displaced.

3.3 Adaptive system design

Generally innovation is represented as a linear sequence from research to extension and adoption. System innovation instead requires an iterative process that can combine backcasting from desired outcomes with continuous diagnosis, co-design, coordinated intervention, monitoring, feedback and adaptation.

The process begins by specifying the outcomes the system should deliver and the constraints it must respect. Diagnosis then identifies the interactions and structural conditions that prevent those outcomes from being achieved. Researchers, producers, firms, service providers, consumers and policymakers can jointly design interventions that are technically feasible, economically viable, environmentally sound and institutionally credible.

Monitoring is therefore part of the design rather than an assessment added at the end. Artificial intelligence and other digital technologies can integrate field observations, animal health records, environmental measurements, market data and consumer information. Their value lies not simply in generating predictions but also in revealing interactions and supporting timely adjustment. Feedback is likely to require changes to the technology, delivery model, incentive structure or even the original objective. System innovation therefore assumes that complex interventions can produce unexpected effects and that sustained performance depends on the capacity to learn, adapt and coordinate.

Agricultural system innovation integrates complementary capabilities across disciplines (*X*-axis), connects activities across the agrifood chain (*Y*-axis), and coordinates interventions across spatial and organizational scales (*Z*-axis). At the core, an adaptive cycle of shared goals, diagnosis, co-design, coordinated intervention, monitoring and feedback enables continuous learning and system transformation (Fig. 1).

4 Agriculture Green Development as an evolving case of system innovation

The year 2015 marked two important developments relevant to the emergence of Agriculture Green Development (AGD): the adoption of the United Nations Sustainable Development Goals and the elevation of green development in China to a strategic priority by the Government of China. China subsequently incorporated green transformation into agricultural development, and the concept of AGD and its associated policy framework were further articulated in 2017, facilitating transdisciplinary research and system innovation in agricultural science. The concept of AGD was originally formulated to reconcile environmental sustainability with agricultural development by restructuring relationships

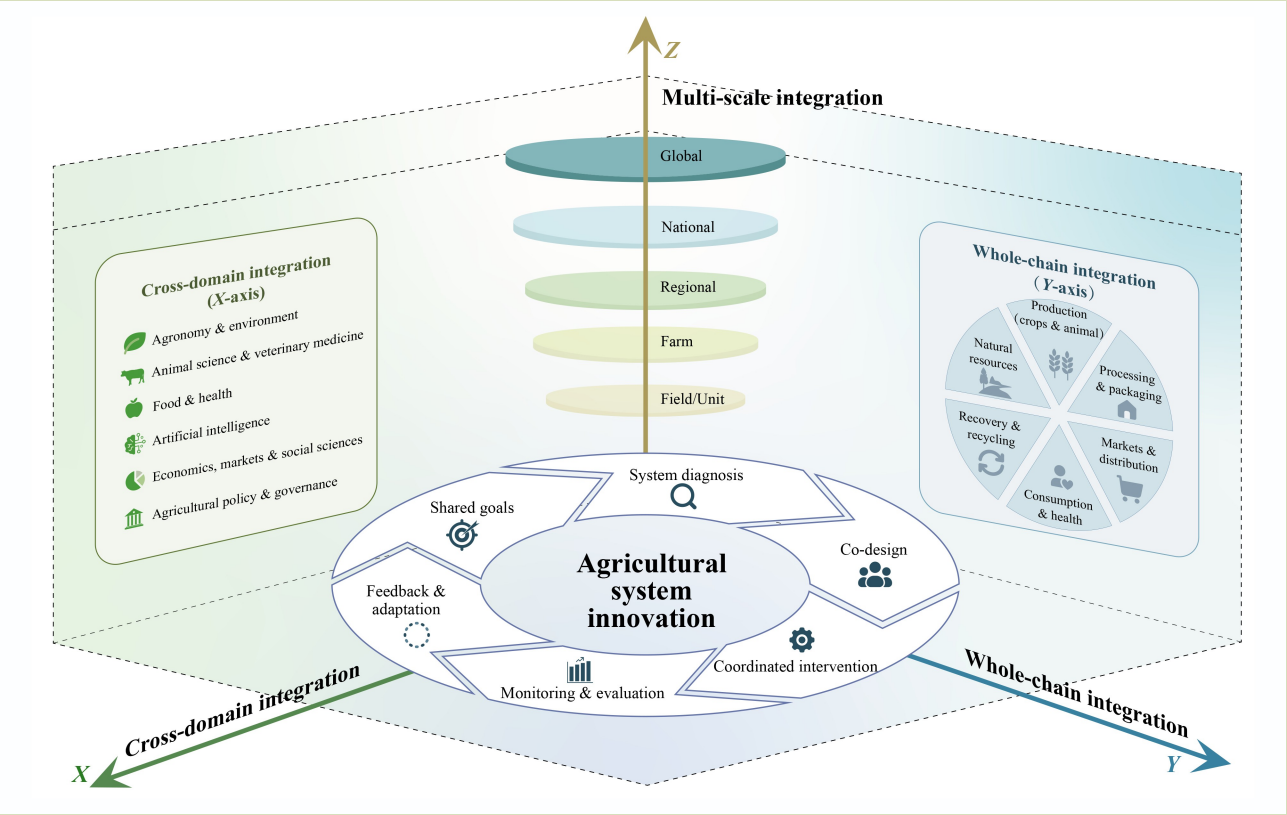


Fig. 1 Three dimensions of agricultural system innovation.

between crop and animal production, natural resources, food processing and consumption. It links environmental performance and food quality with productivity, resource efficiency, and human welfare, while emphasizing interdisciplinary innovation, whole-chain improvement and region-specific solutions[1].

Subsequent work made this system logic more explicit. The AGD innovation framework organizes agricultural transformation into four interconnected subsystems: green crop production, green integrated crop-animal production, green food and industry, and green ecological environment and ecosystem services. Importantly, innovation is also expected to occur at the interfaces between these subsystems. The framework has increasingly emphasized multi-objective coordination, multiple stakeholder participation and region-specific implementation[2].

Three features are especially relevant to the system-innovation framework proposed here. First, AGD shifts the focus from isolated green technologies towards coupled production and environmental systems. Nutrient management, for example, is not treated simply as a fertilizer-use problem but rather as the core of soil health, crop nutrient demand, fertilizer design, animal feeding, manure recycling, spatial patterns of production and environmental thresholds. Crop and livestock systems are connected through feed and nutrient flows, while environmental outcomes are considered across soil, water and air.

Second, AGD extends the system boundary from production to consumption. Its objectives include the provision of safe, nutritious and high-quality food, which requires production systems to respond to dietary needs and credible market signals. Standards, certification and value-chain arrangements can translate social demand into production requirements. Consumers therefore influence the direction of change, while public policy remains necessary where environmental and health benefits are not fully reflected in market prices or where affordability, information or access constrain choice.

Third, AGD links research with regional action. The relevant interactions between farmers, service providers, enterprises, governments and ecological conditions cannot be fully understood or tested through independent experiments alone. Regional platforms, including Science and Technology Backyards (STB) model, provide mechanism for long-term engagement, joint problem-solving, technology adaptation, and feedback from practice. The STB approach places researchers and students closer to farmers and local production conditions, creating opportunities to combine scientific knowledge with local experience and iteratively adapt technologies to real-world constraints.

AGD can therefore be understood as an evolving real-world case of system innovation, in which knowledge, production, consumption and governance are progressively connected. At the same time, it illustrates the distinction between system innovation and engineering implementation. System innovation determines the outcomes, boundaries and interactions and institutional conditions that should guide redesign. Engineering agriculture organizes the technical and institutional components into solutions that can function under real conditions, and can be adapted and scaled[3].

5 Priorities for advancing agricultural system innovation

Three priorities should guide future research and practice.

First, agricultural research needs shared system goals and a limited set of compatible metrics. Evaluation should cover the main outcomes relevant to the intervention and identify where costs and benefits arise and how they are distributed. The purpose is not to require every project to measure everything but rather to prevent major trade-offs, spillovers or distributional effects from remaining outside the analytical frame.

Second, research should focus more directly on interactions, feedbacks and unintended consequences. Greater attention is needed at the interfaces between crop and animal production, environment and health, production and consumption, digital information and decision-making, and technology and institutions. Material-flow analysis, life-cycle assessment, value-chain analysis, socioeconomic modeling and stakeholder participatory methods can be combined to determine whether an intervention solves a problem at the system level or merely shifts it elsewhere.

Third, system innovation requires regional platforms for co-design and adaptive learning. Long-term living laboratories and demonstration regions can bring together universities, producers, enterprises, service providers, public agencies and consumers under real production and market conditions. Such platforms should compare alternative system designs, monitor multiple outcomes, and revise technical and institutional arrangements as evidence accumulates. Demonstration and learning sites operating at appropriate scales, from county and watershed to provinces, can help bridge the gap between science innovation and practice transition.

6 Conclusions

The major challenges of agriculture arise from interactions between natural resources, crops, animals, food, health, markets, digital systems and public institutions. They cannot be resolved through isolated improvements within individual disciplines or stages of the food chain.

Agricultural system innovation provides an integrated framework for identifying what should change, which components need to be connected, and which outcomes should guide evaluation. The six major areas of agricultural research contribute complementary capabilities to this task but their value depends increasingly on how effectively those capabilities are connected across system boundaries and decision processes. Future progress will depend less on adding innovations to existing systems and more on organizing knowledge, technologies, incentives and collective action around coherent multidimensional system performance.

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