HEAD IN THE CLOUD

Challenging the false promise of digital agriculture and cultivating innovation from the ground up

iPES FOOD
INTERNATIONAL PANEL OF EXPERTS ON SUSTAINABLE FOOD SYSTEMS

HEAD IN THE CLOUD

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Credit: L'Atelier Paysan

KEY MESSAGES

"Innovation" has become a buzzword, often presented as a cure-all for every problem in food and farming systems. Today, it has become synonymous with the rapid development of AI, precision agriculture, bioengineering, and automation. **Yet innovation is deeply political, and reproduces specific systems of power.**

Agricultural innovations are shaped by particular social, ecological, economic, and political systems, and tend to reproduce the paradigms in which they were developed – whether extractive or inclusive; corporate-driven or farmer-led. What counts as innovative, whose knowledge matters, which solutions are considered appropriate, and who should benefit from agricultural innovations are all political choices.

A powerful new alliance between Big Tech corporations (including Google, Microsoft, Amazon, and Alibaba) and Big Ag firms is rapidly gaining control of farming under the guise of innovation. These Big Tech titans are providing cloud platforms and AI-driven decision tools being integrated into all parts of industrial agriculture, from seeds to chemical inputs to machinery. As a result, they are shaping what technologies are developed, how food production decisions are made, and what the future of farming looks like.

Public institutions and private actors are investing billions in these Big Tech agricultural innovations – framed as indispensable for productivity, soil and crop health, labour, and climate challenges. But they are betting on the wrong model.

Corporate-led digitalization of agriculture is failing to deliver ecological resilience, equity, or sustainability. Instead, it is deepening dependency on risky corporate schemes and locking agriculture into high-cost, high-energy, and high-input pathways. These innovation models tend to be extractive, expensive, polluting, and misaligned with farmers' real needs.

Big Tech and Big Ag firms are turning farmers' knowledge and work into profit, while farmers lose control over their own data. Digitalization is outsourcing farmer decisions to distant algorithms, with little accountability. Control over data is thus becoming a new source of power and profit in agriculture.

Continuing along this pathway risks leaving us with declining ecological resilience, rising farmer debt and bankruptcies, loss of rural jobs, erosion of farmer knowledge and autonomy, widening inequality between farms and between Global North and Global South countries, and shrinking democratic oversight over food systems.

At the same time, often hidden from view, farmers, Indigenous Peoples, and local communities are pioneering real innovations from the ground up. From ecological pest management approaches to peasant seed systems, these innovation systems are already delivering tangible benefits for climate resilience, biodiversity, livelihoods, and local economies.

Decentralized and grassroots innovation systems tend to prioritize affordability, adaptability, and repairability, while being grounded in local knowledge, lived experience, and collective learning. They recognize farmers, Indigenous peoples and local communities as innovators, ensuring their control. They work with rather than against ecological processes, are locally appropriate, and prioritize autonomy, resilience, diversity, and care – over narrowly defined productivity and efficiency gains.

Yet these innovation systems are systematically undervalued and underfunded. Public R&D, regulatory frameworks, and investment flows overwhelmingly favour corporate-led innovation models, sidelining approaches that are better aligned with farmers' realities and ecological resilience.

Innovation systems can and must be reimagined to support just and sustainable food systems. **We must talk about, fund, and govern innovation differently.** We need to expand what counts as innovation, and shift who drives it.

Reclaiming innovation for people and planet requires:

1. Strengthening public policy for responsible and just innovation,
2. Channeling research and funding towards sustainable, bottom-up initiatives,
3. Breaking up the power of Big Tech and Big Ag,
4. Changing the narrative on innovation.

METHODOLOGY & EVIDENCE GATHERING

Our analysis is grounded in 34 semi-structured interviews and numerous conversations conducted with academics, farmers, and representatives from civil society organizations (CSOs) across world regions. We are also grateful to the research team at the Farmers' Seed Network (FSN China) for supporting a survey and group interviews with 22 of their members across 9 provinces in China.

The report also incorporates a thorough review of diverse knowledge sources, including academic publications, NGO reports, working papers, and evidence collected by practitioners on the ground, focusing on themes related to innovation and technology in agriculture.

We welcome the growing body of literature cataloguing evidence on bottom-up innovation processes and agroecological innovations, and their impacts on food farming systems, including the Grassroots Evidence for Agroecology database, the Grassroots Innovation Assembly Innovation Database, the McKnight Foundation Global Collaboration for Resilient Food Systems' Resource Library, amongst many others.

INTRODUCTION | THE POLITICS OF INNOVATION: WHO SHAPES FARMING SYSTEMS TODAY?

In the Peruvian Andes, a network of family farmers is pioneering a model to protect the genetic diversity of more than 1,000 local potato varieties. By combining traditional seed-saving practices, collective decision-making models, and formal benefit-sharing agreements with voluntary seed companies, AGUAPAN is improving community food security, strengthening local climate resilience, and making the rights of custodian farmers more visible in decision-making processes on genetic resources.[1]

In France and Belgium, the Atelier Paysan and Fabriek Paysanne cooperatives are bringing together farmers to co-design tools adapted to peasant agriculture and train them in basic tool building and repair. These initiatives aim to reduce reliance on expensive, proprietary technologies and counter growing corporate control over agricultural machinery and inputs by fostering a more self-sufficient and dignified approach to farming.[2]

In China, the Farmers' Seed Network (FSN) is connecting rural communities and national research institutions to preserve agrobiodiversity. Through community seed conservation, sustainable natural resource management, and farmer-researcher collaboration, the FSN is demonstrating how on-farm biodiversity can strengthen food and nutrition security, improve rural livelihoods, and support climate change adaptation.[3]

Around the world, farming, fishing, pastoralist communities, and Indigenous Peoples are navigating immense pressures, from weathering climate-related shocks to erratic market fluctuations, balancing immediate needs with those to produce food more sustainably. Initiatives like those above represent a proven process of innovation in food and agricultural systems: often built out of necessity, **farmers and communities drive the development of innovations rooted in lived experience, knowledge exchange, and mutual support.**

These communities are continuously innovating, finding new ways to improve, adjust, and pass down the tools and practices needed to meet ever-changing conditions.

Yet these stories very rarely make the headlines and are often sidelined by a very different narrative of what agricultural innovation is today. **To many, "the transformative power of innovation" lies almost exclusively in the digitalization and bioengineering of agriculture** – with artificial intelligence (AI), automation, genetic engineering, and precision agriculture frequently invoked as universal solutions to achieve food security and food system sustainability. In early 2025, 150 Nobel and World Food Prize Laureates released an urgent call to develop "moonshot" technologies to boost food production to ensure food security.[4] Of the 32 "most promising innovations" highlighted in the 2023 UN Food and Agriculture Organization (FAO) stocktake of emerging agrifood innovations, over 70% were digitally driven technologies.[5]

Digital innovations in particular are increasingly framed by policy-makers, international institutions, and private actors as a key part of a sustainable transition.[i,6] This framing positions digitalization as the most obvious, if not inevitable, approach to reach food system sustainability and tackle climate change.[7] In line with this belief, governments and intergovernmental bodies worldwide are rapidly putting in place the policies and strategies to accelerate the digitalization of agriculture.[8] Already, the World Bank has financed USD 1.15 billion in loans to fund digital agricultural projects in 36 countries,[9] while the European Union has financed over 200 million euros for digital agritech research and development through its Horizon 2020 program.[10]

i One prevalent example of this in public discourse is around the "twin transition" (i.e., the combination of the digital and "green" transition agendas). See Joint Research Centre. (2022). Towards a green & digital future.; OECD. (2025). Quantifying digital innovation for the twin transition.; UNCTAD. (2023). Twin transitions for global value chains – green and digital.; World Economic Forum. (2022). What is the 'twin transition' - and how can it speed sustainable growth?

WHAT COUNTS AS INNOVATION TODAY AND WHO DECIDES?

Crucial to any discussion on innovation in food systems is the understanding that innovation is never value-neutral, but inherently political. Every innovation is embedded within a specific pathway that has its own vision and set of assumptions about what food and agricultural systems should look like and who they serve. As a result, innovations themselves can be used to reinforce the systems in which they are developed and deployed.[11] (See Box 1 for definitions.)

BOX 1

DEFINING INNOVATIONS AND TECHNOLOGY

In this report, an **innovation** is understood as "a new or improved product, process, or practice brought into use by individuals or organizations in a specific context to meet needs differently than before, or increase effectiveness, competitiveness, resilience to shocks, or environmental sustainability."[12] Innovation can be social, technological, and/or ecological, and reflect knowledge, practices, norms, and ways of organizing. Innovation can involve small, coincidental, or spontaneous adjustments (e.g., a farmer choosing to water plants differently), incremental or intentional developments, or breakthrough inventions that shift societal behaviours (e.g., the first smart phone) – all contributing to overall change to larger agricultural systems.

Food systems, and agriculture in particular, have a long and diverse history of innovation, driven by necessity, curiosity, and a spirit of inherent creativity and experimentation to meet our needs. The role of innovation in food and agricultural systems is complex, involving numerous interactions between social, ecological, institutional, and knowledge systems and between a wide diversity of actors.[13] Innovation in agricultural systems is also neither new nor linear, and has been heavily shaped by historical processes.[14]

Innovation systems refer to dynamic interaction between people, processes, and institutions that contribute to the development and use of specific innovations.[15] When innovations are widely adopted or scaled, they are often accompanied by other types of change – whether new distribution channels or networking models – that facilitate their uptake. Similarly, without the appropriate support structures, such as community support, commercialization pathways, subsidies, or policy incentives, many promising innovations struggle to gain traction. Innovation systems shape how and which innovations are created and succeed, and who benefits and loses from them.[ii] (See Box 2 for more on technology lock-ins.)

Innovation pathways refer to the trajectory that shapes the development of specific products or practices. It describes how innovations emerge, develop, and are used within a given context. A pathway emphasizes the choices made along the way (priorities, values, etc.), the power relations that shape them (e.g., who does and does not have agency to shape choices), the impacts of the innovations it creates, and how these dynamics enable or constrain possibility.

ii This report also draws from literature on "socio-technological configurations" (STCs) to understand the political economy of technology and innovation (e.g., how certain actors, technologies and systems are institutionalized and how power is consolidated). In scientific literature, STCs are defined as the interactions between people, organizations, and technologies that shape and are shaped by each other, influencing the development, adoption, and impact of technological innovations. See Heiberg, J., Truffer, B., & Binz, C. (2022). Assessing transitions through socio-technical configuration analysis–a methodological framework and a case study in the water sector. Research Policy, 51(1), 104363.

While farmers, Indigenous Peoples, local communities and community groups historically drove agricultural innovation, **actors and sectors outside of agriculture have gradually played a role in innovation processes, including public and private research institutions, big agribusinesses, multinational corporations, and financial investors.** In the mid-1800s, the process of innovation was formalized inside and outside of agriculture. In the Global North, professional researchers and scientists began to replace farmer-driven experimentation, supported by the expansion of public and private university research programs and agricultural extension services. This top-down model of innovation was then imposed onto colonies in the Global South, where agricultural R&D focused heavily on the development of a handful of cash crops for export into imperial economies.[16]

At the same time, **the rise of a few large agribusinesses fundamentally reshaped how innovation is understood and how it can occur.** The advent of the tractor, the mainstreaming of chemical fertilizers – and later pesticides – allowed a handful of machinery, fertilizer, seed, and pesticide companies to gain significant power and influence over the food system. By the mid-20th century, these firms had accrued the economic and political clout to shape research agendas, public policy, and markets in ways that reinforce their dominance – particularly through the use of intellectual property rights.

More recently, **big technology companies have identified the agricultural market as a major financial opportunity, with massive ripple effects on the power, influence, and decision-making over how our food is produced.** Over the past few decades, the largest tech firms have moved in to collaborate with major farm machinery and agrochemical companies – including Bayer, BASF, Corteva, Syngenta, Nutrien, John Deere, AGCO, and CNH Industrial –[17] to integrate farming equipment, agrochemical inputs, and data-driven tools under precision agriculture. Tech giants, including Microsoft, Amazon, Google, Alibaba, and Meta, are leveraging their advancements in cloud storage and AI tools to develop platforms and data processing software to store and analyze field and weather data (see Figure 1).

Credit: Farmers' Seed Network (China)

FIGURE 1

BIG TECH ENTERING THE AG PLAYING FIELD

This figure illustrates some of the major collaborations between leading technology companies and key agribusiness corporations and/or public institutions. The list is not exhaustive as Big Tech actors are also engaging with a broader range of public, private, and non-profit organizations. (For example, Google and Alibaba Cloud are collaborating with S&P Global, IBM with The Nature Conservancy, Heifer International, and Plan21 Foundation for Sustainable Human Development, and Amazon Web Services with WeFarm, amongst others.)

Meanwhile, technology startups are also working to provide new hardware and software platforms required to digitize agriculture and are increasingly being bought up by major agrochemical and machinery companies. In 2023, the global digital farming market was valued at USD 24.1 billion and is projected to reach up to USD 71.96 billion by 2032.[18] In 2024, McKinsey estimated that AI could contribute up to USD 250 billion in savings to agriculture by lowering labour and input costs, and improving yields and sales growth.[19]

Industry narratives portray these companies as "disruptors" or "disruptive innovators", yet many studies demonstrate how these companies often develop technologies designed precisely so that dominant systems can remain intact, and reinforce corporate control.[20,21]

For example, the agritech sector is rife with large firms that act as powerful incumbents to start-ups, steering innovation through investments and acquisitions, as well as through more indirect means (e.g., shaping industry conference agendas or the priorities of incubator and accelerator programs).[22]

As a result, the "technology power" gained by dominant agribusiness and tech actors is not only allowing them to decide what innovations are developed and scaled, but also to stifle the ones that do not align with their interest.[23] Increasing corporate concentration, together with the professionalization of R&D, has driven a process of innovation defined by technological development in the lab, transfer to commercial producers and buyers, and top-down dissemination by external advisors and sellers to farmers and communities – particularly to wealthier farmers in wealthier regions. (See Box 2.)

BOX 2

CONSTRAINING FARMERS' CHOICES: TECHNOLOGICAL LOCK-INS AND TECHNOLOGICAL TREADMILLS

Our analysis is informed by the concept of technological lock-ins and technological treadmills, dynamics that help to expose how farmers' choices are often constrained by dominant innovation systems:

Technological lock-in occurs when the widespread adoption of a technology creates increasing returns to its continued use, making it progressively more difficult to shift away from it.[24] A technology can gain market dominance even when known costs and problems are associated with it. In agricultural systems, once a farmer becomes involved in the use of a certain technology, it often becomes too complex and costly to change course, compelling them to adopt subsequent innovations to remain viable.[25]

Some technologies can have unforeseen consequences and introduce new problems, prompting the development of further technologies that build on the same underlying technological pathway and perpetuate a never-ending **technological treadmill**.[26] Technological adoption cycles typically allow for short-term efficiency and productivity gains that drive up demand and push down prices, before new challenges drive the need for more technological innovation.[27] In agricultural systems, farmers can be pressured to grow and/or adopt new technologies to remain competitive,[28] also referred to as the trend to "get big or get out".[iii] Late adopters or those unable to benefit from expensive new technologies (due to farm size and/or income) often cannot keep up with the pace of change, and are thus forced to sell their assets to wealthier farms, ultimately resulting in fewer but larger farms.

iii This phrase was reportedly coined by former US Secretary of Agriculture, Earl Butz, in the 1970s, during which he urged farmers to transition towards large-scale commodity crop production.

WHY RETHINK INNOVATION AND WHAT IS ITS ROLE IN FOOD SYSTEM TRANSFORMATION?

In light of current trends, **setting a clear pathway for food systems sustainability requires us to examine what we mean by "innovation" today, including the ideas, actors, and practices associated with it.** Failing to question current assumptions on innovation means we risk overlooking and delegitimizing the diverse approaches already working on the ground – often through farmer- and community-driven processes.[29] We also risk failure to fully evaluate the social, ecological, economic, and political impacts of dominant innovation pathways.

This report offers a critical lens on the innovation systems shaping agriculture and whose consequences ripple across the entire food system. We adopt a power-sensitive lens to examine how agricultural innovation is being defined, whose interests are shaping dominant narratives, and which pathways are being promoted – or sidelined – as a result. We ultimately ask: **what kind of innovation systems do we need to meaningfully support sustainable and equitable food and agricultural systems?**

We particularly emphasize the role of small- and medium-scale farmers, who have historically played a leading role in developing innovations, and who face disproportionate risks under dominant innovation pathways through the tools and practices they are expected to adopt and the decisions they are expected to make. In this report, we use the term "innovation" strategically, as a way to engage in policy, institutional, and scientific spaces where the word holds power to define what counts as legitimate and what is deemed worthy of support. At the same time, we recognize the limits of this language.

The term "innovation" gained prominence in the post-World War II period to describe technological change designed to fuel economic growth, and has since acquired a subjectively positive connotation.[30,31]

A number of scholars and movements already challenge the innovation frame, arguing that it is rooted in Western, capitalist, and colonial worldviews.[32] They highlight that innovation narratives tend to (deliberately or inadvertently) reproduce gendered, racialized, and class hierarchies, and privilege market-driven growth over social and ecological needs.[33] Since the 1970s, this small but growing movement has called for a more expansive and inclusive understanding of innovation that recognizes and values knowledge diversity, the social and ecological dimensions of transformation, and expands the scope of creativity and imagination for change.[iv,34] Some analyses go further, calling for a shift away from innovation discourse altogether on the basis that accepting innovation as a societal imperative risks privileging those who already hold power, reinforcing dominant agendas, narratives, knowledge systems, and practices.[v] We therefore use the term with caution, always asking innovation of what, by whom, for whom, and in what context, recognizing that it always rests on normative assumptions.

iv For example, recognition of Indigenous Technical Knowledge (ITK) and its role in agricultural innovation began in the 1970s as a push back against the dominance of Western-centric views of science and knowledge systems in international development programs, agricultural policy, extension services, research, and more. See Howes, M., & Chambers, R. (1979). Indigenous technical knowledge: Analysis, implications and issues. The IDS Bulletin, 10(2), 5-11; The Farmer First movement of the 1980s placed farmers at the center of research and innovation and further marked a shift in agricultural and research practices. See: Rhoades R.E. and Booth R.H. (1982). Farmer-back-to-farmer: a model for generating acceptable agricultural technology. Agricultural Administration 11, 127–137.

v As Anderson and Maughan suggest, "we recommend that advocates of agroecology – and other holistic, political, and radical proposals for change – avoid the innovation frame in debates on policy, research, and visioning for the future, wherever possible." See Anderson, C., and Maughan, C. (2021). "The innovation imperative": the struggle over agroecology in the international food policy arena. Frontiers in Sustainable Food Systems, 5.

HOW THIS REPORT IS STRUCTURED

In agricultural systems, challenges are felt most tangibly on the farm, where farmers and local communities confront unpredictable ecological, social, and economic changes on a daily basis. In Sections 1-3, we consider three common agricultural production-related challenges shared by farmers around the world and around which innovation efforts are often centered. For each challenge, we examine two different types of agricultural innovations being put forward: one that has gained political and financial traction today and one already widely used around the world, but that is often overlooked by mainstream approaches. These include:

1. **how to ensure soil health** through the lens of remote sensing and manual tools;
2. **how to protect crops from pests and disease** through precision spraying technologies and ecological pest management, and;
3. **how to ensure climate adaptation and resilience** through gene-edited seeds and peasant seed systems.

In each case, we ask which actors are promoting them and what their impacts are. To guide this analysis, we apply a common assessment framework, which builds on and synthesizes existing principles and frameworks used to evaluate innovations in food and agricultural systems (see Box 3.) Building on this prior work, our framework consolidates key criteria into five interrelated dimensions and puts forward a consistent set of questions to assess the multiple impacts of agricultural innovations.

This analysis is not meant to be exhaustive, nor does it aim to provide a direct comparison between different innovations. Instead, we aim to highlight the diversity of solutions available to address common agricultural challenges and reveal the broader systems and pathways different innovation choices reinforce. Because the innovations we examine below also widely differ, not all dimensions carry equal weight in every case.

The five dimensions for our analysis include:

1. **Ecological sustainability:** How does the innovation interact with natural processes? How does it affect ecosystem health, (agro) biodiversity, and/or climate resilience? Does it cause environmental externalities, and if so which ones?
2. **Equity, livelihoods, and labour:** How does the innovation intersect with gender, class, race, culture, and other socio-cultural factors? Who benefits from it, who bears the risk, and whose labour does it rely on? What implications does it have on the health and livelihoods of those who use it (e.g., farmers, peasants, Indigenous Peoples, local communities)?
3. **Autonomy and control:** Who owns, controls, and governs the innovation? Is it accessible, affordable, adaptable, and (when relevant) repairable? How does it impact farmers' and local communities' dependence on external inputs, services, and actors?
4. **Knowledge and skills:** Whose knowledge and which knowledge system(s), skills, and practices are valued, supported, or marginalized? How does the innovation impact how learning and knowledge exchange occur?
5. **Implications for power:** In which innovation pathway(s) is the innovation embedded, and which paradigms does it normalize? How does that pathway both reflect and influence policy decisions and the distribution of power in food systems?

Section 4 takes stock of how and whether different innovation systems support just and sustainable food systems. We also highlight areas where tensions remain underexplored and conclude with levers for strengthening the innovation systems able to foster more equitable, sustainable, and resilient food systems.

Lastly, we acknowledge that innovation choices are closely tied to ensuring decent livelihoods.[vi] Farmers and communities are diverse, and their priorities, perspectives, and experiences vary significantly based on region, farm size, gender, and socio-economic, political, and environmental context. What motivates a farmer or community to adopt a particular tool or practice is often multifaceted and shaped by a broad range of values, priorities, and constraints: these can be technical (e.g., ease of use), structural (e.g., availability, policy-driven incentives, technological path dependency), or philosophical, spiritual, or social in nature (e.g., animal welfare, environmental concerns, care and dignity).[vii] In addition, we also recognize that farmers rarely operate exclusively within one innovation system, and are often embedded in multiple systems at the same time to navigate costs, availability, and access constraints, or manage unexpected shocks.

BOX 3

FRAMEWORKS TO ASSESS INNOVATIONS

Various principles and frameworks underpin our analysis of what characterizes the agricultural innovations and innovation systems in line with sustainable food systems. These frameworks include those of A Bigger Conversation (2023), IFOAM (2022), the UK Soil Association (2021), the STEPS Center (2015), and DEMOS (2006). We also draw heavily on the 13 Principles of agroecology defined by the High Level Panel of Experts on Food Security and Nutrition (HLPE)[35] and Maywa Montenegro de Wit's 6 Principles for Technology Sovereignty.[36]

These frameworks build on different fields of studies and approaches, including environmental sciences (e.g., on agrobiodiversity), agricultural economics (e.g., on costs and income), political economy (e.g., on corporate concentration), labour studies (e.g., on farmworkers' working conditions and skills), and science and technology studies (e.g., on the politics of knowledge and the possibilities granted to users in choosing a technology).

The table on the next page summarizes the key concepts emphasized across these frameworks and highlights the elements we have integrated into our own assessment framework:

vi We also recognize that many other challenges could have been identified (e.g., around water use, energy use, on-farm food loss prevention, animal health and welfare), or other more recent innovations selected.

vii The complexity of these choices is understood in science and technology studies (STS) through the concept of "affordances", i.e., the possibilities and limits that different technologies offer to different users. Recent STS research highlights that the adoption of an innovation or technology is heavily shaped by specific values, material constraints, or power relations. See Glover, D. (2022). Affordances and agricultural technology. Journal of Rural Studies, 94, 73-82. See also Ditzler, L. et al. (2018). Affordances of agricultural systems analysis tools: A review and framework to enhance tool design and implementation. Agricultural Systems, 164, 20-30.

Framework	Key concepts
A Bigger Conversation (2023)	• Provides a framework and set of criteria for farmers to assess technologies based on practical, philosophical, and political questions. • Key considerations for assessing tech includes demonstrable need and clear purpose, full ecological and social footprint, affordability, contextual relevance, and adaptability, support for knowledge, learning, connection, and community, compatibility with diversity and complexity, supports autonomy, agency and choice, fair distribution of risks, inclusive and collaborative development processes, transparent ownership, participatory governance and comprehensive oversight, and control, awareness of embedded societal assumptions behind a tech.
IFOAM (2022)	• Provides a set of principles for the development of Information and communication technology (ICT) initiatives Informed by the HLPE's 13 principles of agroecology. • Key principles emphasize cultural and context specificity, participatory research and knowledge, ecological impact and energy efficiency, resilience to avoid technological lock-ins, farmer-driven innovation, appropriate use and governance of new technologies.
UK Soil Association (2021)	• Provides indicators for good governance of agricultural technologies. • Key principles for governance include participatory knowledge generation (farmer-to-farmer, farmer and researcher), accessibility of and farmer control over data, farmer autonomy over decision-making and access to impartial advice, accessibility, repairability, interoperability, adaptability of technologies, comprehensive tech assessments (inc. lifecycle analysis, cost-benefit analysis)
Montenegro De Wit (2021)	• Provides six principles for technology sovereignty drawing on food sovereignty principles. • These include: 1) focusing on technology for people, 2) valuing food providers as tech providers, 3) localizing tech systems, 4) putting control locally, 5) building knowledge and skills, and 6) working with nature.
HLPE & 13 Principles of Agroecology (2019)	• Provides a values-based framework to assess innovations needed for just and sustainable food systems, integrating ecological, social, economic, and political criteria. • As an "innovative approach" to food system sustainability, agroecology can be characterized by 13 principles to guide transformative change, including: (1) Recycling, (2) Input reduction, (3) Soil health, (4) Animal health, (5) Biodiversity, (6) Synergy, (7) Economic diversification, (8) Co-creation of knowledge, (9) Social values and diets, (10) Fairness, (11) Connectivity, (12) Land and natural resource governance, (13) Participation
STEPS Centre (2015)	• Provides 3 dimensional agenda to reorient innovation designed for science and technology to work towards social justice, equity, and environmental sustainability. • Emphasis on direction (i.e., supporting pathways that serve marginalized communities and enables transformative change, over dominant trajectories), distribution (i.e., ensuring benefits, risks, and decision-making shared fairly through inclusive and ongoing participation of key actors), diversity (i.e., ensuring a diversity of innovation approaches to prevent concentration of power, to promote resilience, and protect creativity and experimentation).
DEMOS (2006)	• Provides overview of 2 technological pathways for development, emphasizing the need for context-specific, culturally- and socially-appropriate, and participatory approaches. • Emphasis on public and multi-level governance, prioritization of public support for alternative innovation pathways, inclusive regulation of risk, participatory engagement in science and research, and broad democratization of innovation processes.

1

INNOVATIONS TO ENSURE SOIL HEALTH

Credit: McKnight Foundation

In this section, we examine two innovations related to ensuring soil health: remote sensing and manual tools. While remote sensing technologies centre on generating information about soils through digital systems, manual tools embody the labour, knowledge and physical practices through which farmers directly shape soil health. These two tools allow us to understand how soils can be nurtured and how different innovation pathways impact ecological outcomes, resource use, labour, gender dynamics, knowledge systems, farmer autonomy, and power within food systems.

Healthy soils are the foundation of life. They are living ecosystems, home to millions of organisms and supporting up to 95% of our food production.[viii] Through an interconnected and complex web of activity, soils nurture plants and animals, purify water, support biodiversity, and regulate climate. They are also deeply connected to identity, culture, spirituality, and community. For many rural and Indigenous communities around the world, healthy soil is a source of joy, pride, and connectedness, reflecting a holistic or reciprocal relationship with the land.[37] Humans have worked for centuries to ensure soil health, fertile cropland, and ecosystem resilience.[ix]

However, many human activities and the compounding impacts of climate change are depleting soils worldwide. Today, **up to 40% of land is degraded due to chemical-intensive food production, mining, urbanization, and deforestation**,[38] directly threatening the lives and livelihoods of up to 3.2 billion people around the world.[39] An estimated 24 billion tonnes of fertile soil is lost every year, with the most severe impacts felt in Southeast Asia and Sub-Saharan Africa, where farmland degradation is most widespread.[40]

The industrialization of agriculture has played a major role in scaling up the overexploitation and degradation of agricultural land since the mid-1800s. The more recent and rapid decline of agricultural soils' health can be traced back to the development of the Haber-Bosch process in the early 20th century, i.e., the industrial nitrogen fixation method to produce ammonia required for synthetic fertilizers.[41,42] Changes in dominant soil science underpinned this industrialization by framing soils as inert substrates rather than living ecosystems.[43] In particular, this normalized the continuous monocropping and overuse of synthetic fertilizers and pesticides, causing soil nutrient depletion as well as soil and water contamination worldwide.[x,44] (see Box 4.)

viii The other 5% of food production is largely derived from aquatic systems, and to a lesser extent from soilless production methods (e.g., hydroponic, aeroponic) and lab-grown foods. See FAO. (2022). Soil for nutrition: state of the art.

ix For example, terra preta is a nutrient-rich soil nurtured by Indigenous communities in the Amazon Basin for hundreds – if not, thousands – of years. Terra Preta (also referred to as "dark earth") is made by adding biochar and other organic matter to the soil, improving soil structure, enhancing water retention capacity, and serving as a major carbon sink. Local communities have supported up to 10% of Amazonian soils through terra preta, an area roughly equivalent to the size of Spain. Similar dark earth has also been developed in other regions, including West Africa, where women play a central role in its production and distribution in the fields. See One Earth. (2024, September 27). Biochar: Rediscovering ancient wisdom for modern soil health; Solomon, D., Lehmann, J., Fraser, J. A., Leach, M., Amanor, K., Frausin, V., Kristianson, S. M., Millimouno, D. and Fairhead, J. (2016), Indigenous African soil enrichment as a climate-smart sustainable agriculture alternative. Frontiers in Ecology and the Environment, 14 (2). pp. 71-76; Frausin, V., Fraser, J. A., Narmah, W., Lahai, M. K., Winnebah, T. R., Fairhead, J., & Leach, M. (2014). "God made the soil, but we made it fertile": gender, knowledge, and practice in the formation and use of African dark earths in Liberia and Sierra Leone. Human Ecology, 42, 695-710.

x The production of agrochemicals (i.e., both pesticides and fertilizers) is also a major contributor to greenhouse gas emissions, with the agrochemical industry producing up to 5-6% of emissions worldwide. See IPES-Food. (2025). Fuel to Fork: What will it take to get fossil fuels out of our food systems?

BOX 4

SYNTHETIC FERTILIZERS: DRIVERS OF DECLINING SOIL HEALTH

In the late 1800s, unsustainable harvesting rates of natural fertilizers (primarily guano and bone meal) drove the development of synthetic fertilizers.[45] While different methods to synthesize ammonia emerged in the early 1900s to meet a growing demand, the Haber-Bosch process ultimately enabled the industrial-scale production of synthetic fertilizers.[xi] These fertilizers became an integral part of a burgeoning industrial agriculture system. Alongside improved seeds, mechanization, and synthetic pesticides, synthetic fertilizers would become central to the Green Revolution, the US-driven agricultural modernization effort to extend its influence during the Cold War.

Synthetic nitrogen fertilizer application has increased by 800% since 1961.[46] Promoted by governments and industry for decades, high-income countries account for up to 10 times more synthetic fertilizer application per capita than low-income countries.[47] In 2022, an estimated 185 million tonnes of synthetic fertilizers were used in agriculture,[48] with the FAO projecting a further 50% increase in nitrogen fertilizer use by 2050.[49]

Today, **more than half of nitrogen fertilizers applied globally are not assimilated by plants, polluting air, waters, and soils.**[50] Their use particularly threatens soil health by replacing nitrogen-fixing bacteria and altering biological processes that affect physical structure of the soil (e.g., changing soil PH, reducing soil organic matter).[51] Synthetic fertilizers alone are also responsible for 30% of petrochemical industry emissions,[52] as their application emits nitrous oxide, a greenhouse gas 270 times more potent than CO_2.[53]

In Sub-Saharan Africa, for example, cultivated soils are losing between 30-60 kg of nutrients per hectare every year.[54] Loss of soil biodiversity also leads to the release of soil carbon stores, creating a dangerous feedback loop between climate change and soil degradation.[55] In regions where agricultural land ownership is highly concentrated and/or where smallholder farmers lack secure land tenure, short-term land leases and contract farming models can also fail to incentivize farmers from investing in long-term soil health.[56]

Other factors also contribute to poor soil health. **20% of global farmland is at high risk of soil compaction**, caused by heavy machinery, overtillage, and overgrazing.[xii,57] Poor irrigation practices and over-use of fertilizers are also driving soil salinization (i.e., accumulation of soluble salts) and sodicity (i.e. the excess of sodium ions in soils). Just over 10% of irrigated and rainfed cropland are affected by salinity and sodicity (i.e., high sodium concentration), with subsequent crop losses reaching up to 72% for rice and 68% for beans.[xiii]

xi Invented in 1909, the Haber-Bosch process was commercialized by BASF in 1913. BASF. 1913 / First Ammonia Synthesis Plant. Accessed November 4, 2025.

xi Particularly prevalent in China, Europe, North America, and parts of South America, and Australia, compaction results in stunted plant root growth and lower soil quality, increasing the risk of surface runoff, flooding, erosion, and of reducing crop yields by 50% or more. See Sonderegger, T., & Pfister, S. (2021). Global assessment of agricultural productivity losses from soil compaction and water erosion. Environmental Science & Technology, 55(18), 12162-12171; Shaheb, M. R., Venkatesh, R., & Shearer, S. A. (2021). A review on the effect of soil compaction and its management for sustainable crop production. Journal of Biosystems Engineering, 1-23.

xiii Countries most affected by soil salinity and sodicity include Australia, Argentina, Kazakhstan, the Russian Federation, the United States, the Islamic Republic of Iran, Sudan, Uzbekistan, Afghanistan, and China. FAO (2024). Global status of salt-affected soils. Rome.

Credit: European Space Agency

REMOTE SENSING

Agricultural remote sensing refers to the use of satellites, aircraft (e.g., drones), tractors, and ground-based or handheld devices equipped with sensors to collect data on crops, soils, terrain, and farming landscapes from a distance.[58] These data can then be processed and used by farmers, agribusinesses, governments, and research institutions for land use mapping, environmental monitoring, soil management, crop management, or to support early warning systems to prevent the impacts of extreme weather events and climate variability.

Satellite or aerial sensing often rely on imagery as well as optical, infrared, or microwave sensors and tend to provide low-resolution, publicly available data used to track land use, crop health, soil moisture, and broader environmental changes across large areas.[59,60,61]

Drones or other vehicle-mounted sensors generally carry radar, thermal, hyperspectral, or multispectral sensors that generate higher-resolution and more localized farm-level data on soil moisture levels, organic and nutrient content, soil texture, compaction, degradation, salinity, and potential contamination, but cover smaller areas and tend to be more costly.[xiv,62,63] (See Box 5 for a brief history of remote sensing.)

Proponents of remote sensing highlight these technologies' ability to rapidly and cost-effectively capture images and spectral data at multiple scales without disturbing the soil. They also put forward that the data gathered can then be used to deliver comprehensive close-to real time or real-time soil assessments to guide "informed" and tailored farm management decisions.

xiv The specific soil characteristics picked up by soil sensors are determined by the sensing technology used, which can be mechanical, electromagnetic, or electrochemical. See Gorissen, L., Konrad, K., & Turnhout, E. (2025). Sensors and sensing practices: shaping farming system strategies toward agricultural sustainability. Agriculture and Human Values, 1-19; Abdulraheem, M. I. et al. (2023). Advancement of Remote Sensing for Soil Measurements and Applications: A Comprehensive Review. Sustainability, 15(21), 15444.

BOX 5

A BRIEF HISTORY OF REMOTE SOIL SENSING

Remote soil sensing finds its roots in the aerial photography used for landscape mapping and crop inventories conducted in the US after World War I. As part of improving surveillance tools, remote sensing later evolved through the military and scientific developments around infrared photography made during World War II.[64] Soil sensing technologies have continued to evolve alongside breakthroughs in telecommunication and computing technologies, with satellite-based remote sensing collecting agricultural data since the 1960s.[65] Since the early 2000s, unmanned aerial vehicles (UAVs, i.e., drones) have increasingly been used to monitor and manage crops, water, and soils[66] Advances in cloud computing and telecommunication over the past two decades, particularly the Internet of Things (IoT),[xv] has massively sped up the development of remote soil sensing, by ensuring more stable transmission of data and faster processing.

Uptake of soil remote sensing tools at the farm-level is still largely concentrated in high-income countries and large-scale industrial farms, due to the scale of operation and investment required to use these technologies (see more below). These technologies are now often embedded in precision agriculture machinery and require reliable connectivity, local digital infrastructure, and technical training, which limits their accessibility for smallholder farmers and farmers in the Global South.[67] According to a 2024 McKinsey survey across 4,400 farmers in nine countries, farmers in the US are estimated to have the highest adoption rate for remote sensing technologies at 38%, followed by Brazil (approx. 30% and the EU (approx. 23%).[68]

Rates of adoption heavily rely on public and private investment in internet infrastructure for digital agriculture. Public programs include the USDA's ReConnect Program, connecting rural communities, farmers and businesses with high-speed internet, or Pakistan's Digital Dera initiative, aiming to digitalize agriculture in remote areas of South Punjab.

Private initiatives include Starlink for Agriculture, owned by SpaceX, aimed at bringing precision farming tools (e.g., sensors, drones, data platforms) and high-speed connectivity to farmers in remote areas worldwide.

Impacts on improving soil health practices

Remote sensing aims to contribute to soil health management by providing rapid, reproducible, and real-time data on soil conditions and farming practices. In a second stage, that information is processed and recommendations derived to meet a specific objective (e.g., reduce pesticide use, improve soil fertility).

Therefore, remote sensing itself does not directly shape soil practices; impacts depend on how the data it generates is interpreted and acted upon to influence specific practices. In other words, the potential to improve soil management relies on how remote sensing data is used, by whom, and in which systems.

xv The Internet of Things refers to "a network of physical devices, vehicles, appliances, and other physical objects that are embedded with sensors, software, and network connectivity, allowing them to collect and share data." IBM. (n.d.). What is the Internet of Things (IoT)? Accessed December 5, 2025.

Remote sensing can be used to assess the impacts of holistic farming practices on soil health or to help improve these practices. For example, in Southern Niger and Tunisia, remote sensing has been used to evaluate the impacts of agroecological soil practices and demonstrate their ability to improve soil health.[69] In the US, the Operation Tillage Information System (OpTIS) is an automated system that combines global climate data with satellite-based remote sensing imagery of cover crop development and plant residue to track and analyze the impact of soil health practices over large agricultural areas.[70] Developed by Conservation Technology Information Center, Regrow, and the Nature Conservancy, OpTIS can then assess when and where changes to existing practices might be needed.[xvi] Research in Egypt and India has similarly used remote sensing tools to demonstrate agricultural land degradation over time and make the case for integrated soil fertility management approaches to restore soil health, including agroforestry, organic farming, and diversified cropping methods.[71] Drones have also been used to catalogue and track changes in plant and animal diversity, and to assess the agri-environmental benefits of conservation tillage, cover cropping, crop rotation, and other practices that benefit soil health.[72,73]

However, **remote sensing tools tend to primarily benefit large-scale monoculture farms, due to their integration into precision farming systems.** Precision farming relies on the large volumes of detailed local data collected by remote sensing, aggregated with other types of data (e.g., weather data), and increasingly processed with AI to monitor and guide decisions around resource use and crop management.[xvii] Precision tools are designed to shift away from the one-size-fits-all approach of conventional agriculture and enable more site-specific farm management.[74,75] Embedded in the logic of sustainable intensification,[76] precision agriculture is promoted as a way of "producing more with less" by maintaining or increasing productivity while reducing agrochemical inputs and natural resource use.[xviii]

Remote sensing data is particularly crucial to automated variable rate application technology (VRT), a precision tool designed to optimize irrigation and agrochemical application.[xix,77] Benefits to soil health are meant to arise from improved soil monitoring that can inform farm management decisions on moisture, pH, and nutrient levels, and from reduced fertilizer application.[78,79] For example, Yara, the world's third largest synthetic fertilizer corporation,[80] claims that its nitrogen sensors can improve yields by 12% while reducing fertilizer use by 14%.[81] However, these precision technologies may also risk locking farmers further into costly, fossil fuel-dependent systems that perpetuate the long-term use of synthetic inputs (see Section 2.1 for more).[82]

Impacts on natural resource use and off-farm labour

Remote sensing-based precision tools rely on the continuous capture, storage, and processing of vast quantities of data (i.e., Big Data), and require powerful infrastructure, computing capacity, and high levels of mechanization to operate. As digital data collection increases, so too does the material footprint required to sustain it. These infrastructure requirements are often ignored in the push to digitalize agriculture, framing digital tools as largely immaterial. For example, the language used to describe digital data (e.g., "*the cloud*", "*artificial intelligence*", "*remote sensing*") obscures their physical requirements, whether critical minerals, water, fossil fuels, land, or labour.[83]

xvi Other companies and institutions that have supported the development of OpTIS included the USDA, NASA, Bayer, Corteva, John Deere, Monsanto, The Mosaic Company, and Syngenta, amongst others. See CTIC. (2023). OpTis: Using Remote Sensing Data to Map Conservation Ag Practices.

xvii Precision agriculture grew from the development of the first GPS-guided tractor, produced by John Deere in the 1990s. Deere's GPS-connected tractor was designed to steer automatically based on field coordinates, reducing potential errors or overlaps made by drivers. See Schmaltz, R. (2017, April 24). What is precision agriculture? AgFunderNews.

xviii Some precision systems are designed to operate alongside no-till cropping practices, which can help maintain soil structure and support carbon sequestration. However, in many cases these systems continue to rely heavily on chemical herbicides. See Getahun, S., Kefale, H., & Gelaye, Y. (2024). Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review. The Scientific World Journal, 2024(1), 2126734.

xix VRT refers to technologies that adjust the application rate of inputs based on specific requirements of different areas within a field.

While remote sensing technologies are not wholly responsible for this trend, their integration into precision farming systems ties them to broader digital infrastructure – and particularly on data centers that house the IT needed to store, process, and distribute digital information.[xx]

By 2026, **global data centers' electricity consumption could rival that of Japan's total electricity usage** (1,000 terawatt-hours).[84] Data centers also come with high water demands of clean, treated (often potable) water to cool heat-generating equipment such as storage units or Central Processing Units (CPUs), as untreated water can damage cooling systems. Between 2021 and 2022, Google data centers' water usage rose by 20% and Microsoft's by 34%.[85] In 2024, Google withdrew 9,9 billion gallons of water for its data center, 78% of which was potable water.[xxi,86] In addition, a significant proportion of agricultural data collected is continuously collected and stored, but rarely analyzed or used (also called "dark data"), despite their ongoing environmental cost.

Digital infrastructure also has implications for labour and livelihoods, as **AI-driven and automated decision-making restructures global labor markets, deepening colonial patterns of labour and resource exploitation across the Global South.**[87,88] The invisibilised workers who label data for AI training (e.g., by categorizing, transcribing, labeling, or moderating information) often endure conditions resembling modern slavery, including Brazil, India, Kenya, the Philippines, Uganda, or Venezuela.[xxii,89]

At the same time, evidence from the US shows that data centers are highly automated, and often tend to provide precarious and temporary employment.[90] The minerals required for digital technologies are also overwhelmingly extracted from the Global South and Indigenous lands,[xxiii] and their extraction brings devastating social and ecological consequences, including child labour, forced evictions, land grabbing, and severe pollution, and is the source of many armed conflicts.[xxiv,91]

These dynamics do not suggest that digital data collection is inherently problematic – agricultural and environmental data invariably play a role in supporting on-farm decision-making, especially in a context of climate change (see more below). Rather, they highlight the material foundations on which digital-based agricultural systems (including remote sensing) depend and stress the need to explicitly acknowledge the ecological and social costs associated with digital infrastructure in any balanced assessment of their impacts.

xxi Municipal records from 2023 revealed that Google data centers in The Dalles, Oregon were using more than a quarter of the city's water supply. Across the US, residents in cities hosting new data centers are more frequently reporting lack of access to clean water. And while new technologies are being developed to reduce data centers' high cooling demands, they also represent the latest turn of the technological treadmill. See Farrell, N. (2024, 3 June). Japanese ceramics maker is making a fortune out of AI. Fudzilla; Fleury, M., and Jiminez, N. (2025, July 10). 'I can't drink the water' - life next to a US data centre. BBC News.; Rogoway, M. (2023, February 22). Google's water use is soaring in The Dalles, records show, with two more data centers to come. The Oregonian.; Seitz, P. (2025, 23 September). Vertiv Stock Falls After Microsoft Reveals 'Breakthrough' Chip Cooling Tech.

xxii In 2024, members of the African Content Moderators Union wrote to then–US President Joe Biden, denouncing the systemic abuse and exploitation of African workers by major technology firms. These workers, paid under $2 per hour while working long shifts, provide the foundational labor on which AI companies depend. Companies include Scale AI, a contractor for OpenAI, Meta, and the US military. See Haskins, C. (2024, May 22). The Low-Paid Humans Behind AI's Smarts Ask Biden to Free Them From 'Modern Day Slavery'. WIRED.

xxiii In 2022, Latin America held 58% of global lithium reserves; the Democratic Republic of the Congo produced 68% of the world's cobalt; and Gabon and South Africa together accounted for 59% of manganese production. See Coding Rights. Mapa dos Territórios da Internet. Accessed 2025, August 25.; UNCTAD. (2024). Digital Economy Report 2024: Shaping an environmentally sustainable and inclusive digital future.

xxiv In addition, there are doubts about whether terrestrial reserves are sufficient to support a digitally-driven green transition, pushing governments and corporations to pursue strategies such as deep-sea and space mining in search of new resource frontiers, with further unknown ecological impacts to come. See: UNCTAD. (2024). Digital Economy Report 2024: Shaping an environmentally sustainable and inclusive digital future.

xx An average cloud data center only takes up 0.9 hectares of land. Yet, due to the increasingly complex computation and processing needs of data technologies (and AI in particular), energy efficiency is gained by constructing "hyperscale data centers", which can take up 9 to 18 hectares of land. To date, the US has the most data centers worldwide, while China houses the largest centers. See Berreby, D. (2024, February 6). As Use of A.I. Soars, So Does the Energy and Water It Requires. Yale Environment 360. See also, Coding Rights. (n.d.) Mapa dos Territórios da Internet. (Accessed August 25, 2025).

Impacts on autonomy, knowledge, and control

Remote sensing data can provide farmers with access to a wide range of data, from the granular to the regional landscape level, and is promoted as a way for farmers to make "well-informed decisions."[92] Yet this claim rests on a range of assumptions about what data, knowledge, and experience is needed and viewed as legitimate to manage a farm.

One key assumption is the perception that data is inherently objective, and that accumulating more of the "right kind of data"[xxv] automatically brings about progress through predictability, efficiency, and control. This logic not only justifies continuous datafication (i.e., the process of quantifying and converting information into standardized digital data that can be tracked, gathered, and analyzed), but it also creates hierarchies of evidence that prioritize digital data and tools over the embodied knowledge and lived experiences of farmers, Indigenous Peoples, and local communities. Scholar Kelly Bronson describes this bias as part of a belief in the "immaculate conception of data"[93] – the idea that data exists independently of specific values, assumptions, and interests in how it is gathered, selected, and interpreted.[xxvi]

The result is a model of agriculture that assumes that all problems can be solved through more data and technological innovation, never questioning the promise of the next tool or the need for an additional dataset.

Particularly when integrated into precision tools, remote soil sensing can play a role in reinforcing this model of agricultural development that shifts authority away from farmers and towards external digital systems, reducing farmers to "harvesters" of data. The technical complexity of precision agriculture tools risks deskilling farmers, sidelining their knowledge, and deepening their dependence on external expertise, i.e., requiring actors outside of the food system to process and translate data into non-technical information.[xxvii,94] In this context, remote sensing professionals, data scientists, and even AI, become the main sources of relevant knowledge, imposing new intermediaries between farmers and the knowledge they need to manage their farms.[95] (See Figure 2.)

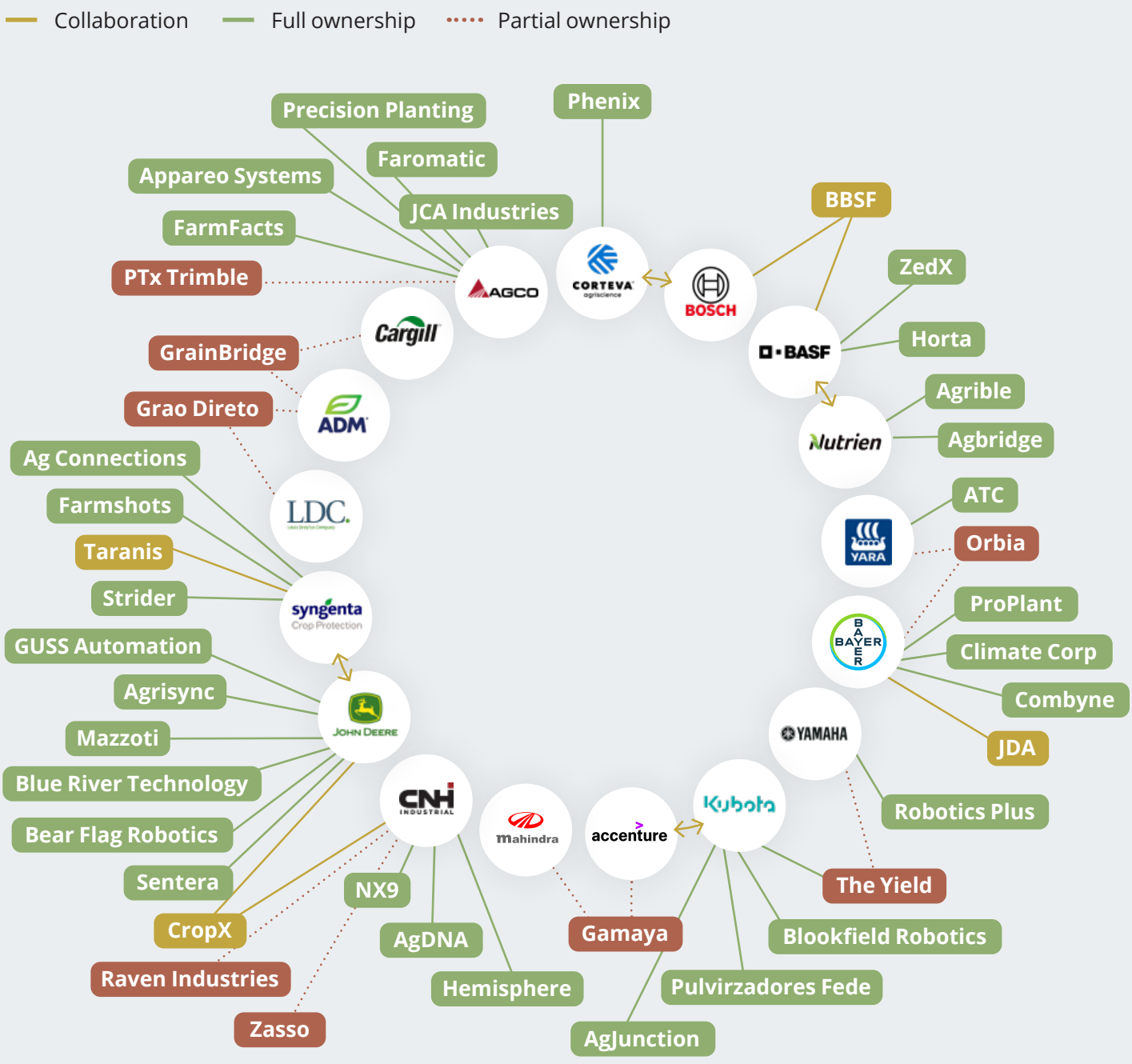
xxv This phrase was used in the Data4SDGs initiative and is quoted in Montenegro de Wit, M., & Canfield, M. (2023). 'Feeding the world, byte by byte': emergent imaginaries of data productivism. The Journal of Peasant Studies, 51(2), 381–420.

xxvi Other scholars have similarly shown that there is rarely such a thing as "objective" data, and that what is measured, how, and by whom can significantly impact data interpretation and policy decisions. See for example, Jerven, M. (2013). Poor Numbers : How We Are Misled by African Development Statistics and What to Do About It. Ithaca: Cornell University Press.

xxvii Research has explored how the agribusiness industry in the US influences farmers' identity to facilitate deskilling and dependency in agriculture. See for example, Carolan, M. (2023). The perilous promise of productivity: Affective politics of farming media and its consequences for the future of agriculture. New media & society, 25(8), 1913-1934; Bell, S. E., Hullinger, A., & Brislen, L. (2015). Manipulated Masculinities: Agribusiness, Deskilling, and the Rise of the Businessman-Farmer in the United States. Rural Sociology, 80(3), 285-313.

FIGURE 2

THE DIGITAL ARMS RACE: HOW BIG AG IS RACING TO BUY UP INFOTECH (2003-2025)



(data from 2002-2023 sourced from Strömberg, L. & Howard, P., 2023)

Public agencies, research institutions, and private companies can already collect, process, and interpret farm data with little to no farmer involvement. For example, France's "MesSatimages" platform combines Sentinel satellite data with historic yield maps to generate advice on fertilizer use for wheat and rapeseed producers; this data is then interpreted by public advisory services before it is delivered as tailored recommendations to farmers.[96] Such initiatives also reflect a broader history of using government extension agents and agro-input dealers as middlemen to promote specific commercial products and prescriptions.[97]

From a feminist political lens, remote sensing's "overhead view" of agriculture (i.e., information literally coming from above) can work to disembed and disembody information. Satellite imagery tends to abstract landscapes from their social contexts – obscuring local knowledge, community dynamics, or the gendered labour that shape agricultural life.[98,99] This top-down view of farming aims to simplify, measure, and control complex social, cultural, and ecological dynamics, reducing the richness of farming into comparable data points that can be optimized.[100,101]

However, remote sensing technologies are not inherently alienating. Gorissen et al. argue that sensing practices in agriculture can either contribute to "oversight" or "insight".[102] *Oversight* refers to using remote sensing to assess soil conditions against a specific optimum, often leading to short-term optimization of practices. By contrast, **remote sensing practices can support on-farm *insight* when "they are used to deepen a holistic understanding of soil ecosystems** and support long-term planning to build more agrobiodiverse systems. For example, as climate change creates greater uncertainty, remote sensing can detect small changes to soils, crops, and weather, providing much-needed predictive insights to manage risk from the farm to the regional level.[103,104] Remote sensing imagery is also increasingly being made publicly available and accessible via mobile apps and open databases, and can act as a complementary tool to expand the information available to farmers and communities to further validate local observations.

When used as one of multiple tools, remote sensing data can be triangulated (i.e., interpreted alongside local knowledge, direct field observation, etc.) **to build more context of local realities and environmental conditions**.

Even before advanced satellite remote sensing, some researchers already combined the use of aerial photography, satellite imagery, oral histories, direct observation, and ecological data to challenge the widespread belief that communities in the forest-savanna zone of West Africa were responsible for local deforestation. Instead, the research showed that local communities were actively contributing to reforestation efforts and exposed the harmful impacts of policies, extension services, and narratives based on a misreading of local human-environment interactions.[105]

In addition, when control and use of data can be fully determined by the farmer and when accompanied by appropriate safeguards around data use, the integration of satellite data with local experience can foster new kinds of knowledge, skills, and exchange between farmers and researchers, farming communities, or for intergenerational learning.[106,107]

More recently, open-source apps co-developed by scientists and farmers, such as LiteFarm and FarmOS, are allowing users to create and annotate their own field and farm maps based on satellite imagery, while incorporating a diversity of ecological and social variables.[108,109,110] There are also ongoing discussions to improve interoperability across tools and platforms, and to broaden what data and knowledge matter in the use of these tools.[111] In these cases, remote sensing becomes one piece of a diverse system for understanding and managing soil, rather than being positioned as inherently better than other existing soil health practices. (See Box 6).

BOX 6

SUPPORTING INDIGENOUS AND COMMUNITY-BASED SOIL KNOWLEDGE

Beyond remote sensing and precision agriculture technologies, a growing number of collaborations between researchers, Indigenous communities, and farmers are demonstrating how traditional soil classifications, Indigenous and community-based knowledge systems, and accessible soil health assessment tools can also provide more affordable and better adapted methods to manage soil health. For example:

- The **Soil Health Toolkit** collects affordable, farmer-centric methods using homemade or affordable tools to test soil structure, water retention, and organic content, allowing farmers to track progress with the implementation of new practices.[112]
- The FAO's **Visual Soil Assessment Field Guides** provide a free resource for farmers to evaluate soils for various agricultural systems (such as annual crops, pastures, and orchards).[113]
- The **Participatory Integration of Knowledge on Indicators of Soil Quality** (InPaC-S) approach and methodological guide was developed from over 10 years of South-South collaboration between farmers, researchers, and extension service organisations across Latin America and Africa. It facilitates bottom-up approaches that integrate rather than compete with local knowledge in soil management, strengthening the relevance and legitimacy needed for new practices to be adopted.[114]

Indigenous and community soil knowledge systems are often complex, location-specific, and relational to agricultural practices – relying on visual signifiers, indicator plants, and collected experience, and involving soil cultures and relations that link people with many aspects of soil life.[115] They are rooted in generations of relationship with local soils, and are intrinsically connected to ancestral soil management practices. These systems can be highly complementary to 'scientific' taxonomies. For example:

- In the Trobriand Islands of **Papua-New Guinea**, local soil classifications (e.g., *kwala, sawewo, dumya*) precisely define suitability for specific crops like yams and taro.[116]
- The Pichátaro people in **central Mexico** view soil as a living being with its own agency, and responsive to climate and environmental changes. Their dynamic classification system shows high complementarity with USDA soil taxonomy.[117]
- Similarly, studies in the Central Llanos of **Venezuela**,[118] northern **Ghana**,[119] and the **Philippines**[120] all found a high correlation between indigenous soil indicators (color, texture, indicator plants) and scientific soil profiles.
- In **Hawai'i**, communities and researchers are revitalizing sophisticated, climate-adapted practices from vast historical agricultural sites like the Kohala Field System. By rebuilding small sections and experimenting, they are re-learning how traditional agricultural systems function and are adapted to their context.[121]
- In **New Zealand**, the integration of Maori knowledge (stories, songs, place names) with soil science has enabled the reconstruction of past cultivation locations, and soil modification and fertilization techniques – reinforcing the connection of contemporary Maori communities to traditional cultivation practices.[122]

Implications for power in food systems

As the World Bank stated in a 2023 report on data-driven agriculture, "data is power."[123] Yet the question remains: power for whom, and for what purpose? The potential for remote sensing to support sustainable soil practices depends on the broader technological systems and governance frameworks which it is embedded in. International institutions, including the FAO, have used open-source remote sensing data for decades to support agricultural development programs, soil monitoring, and land use planning.

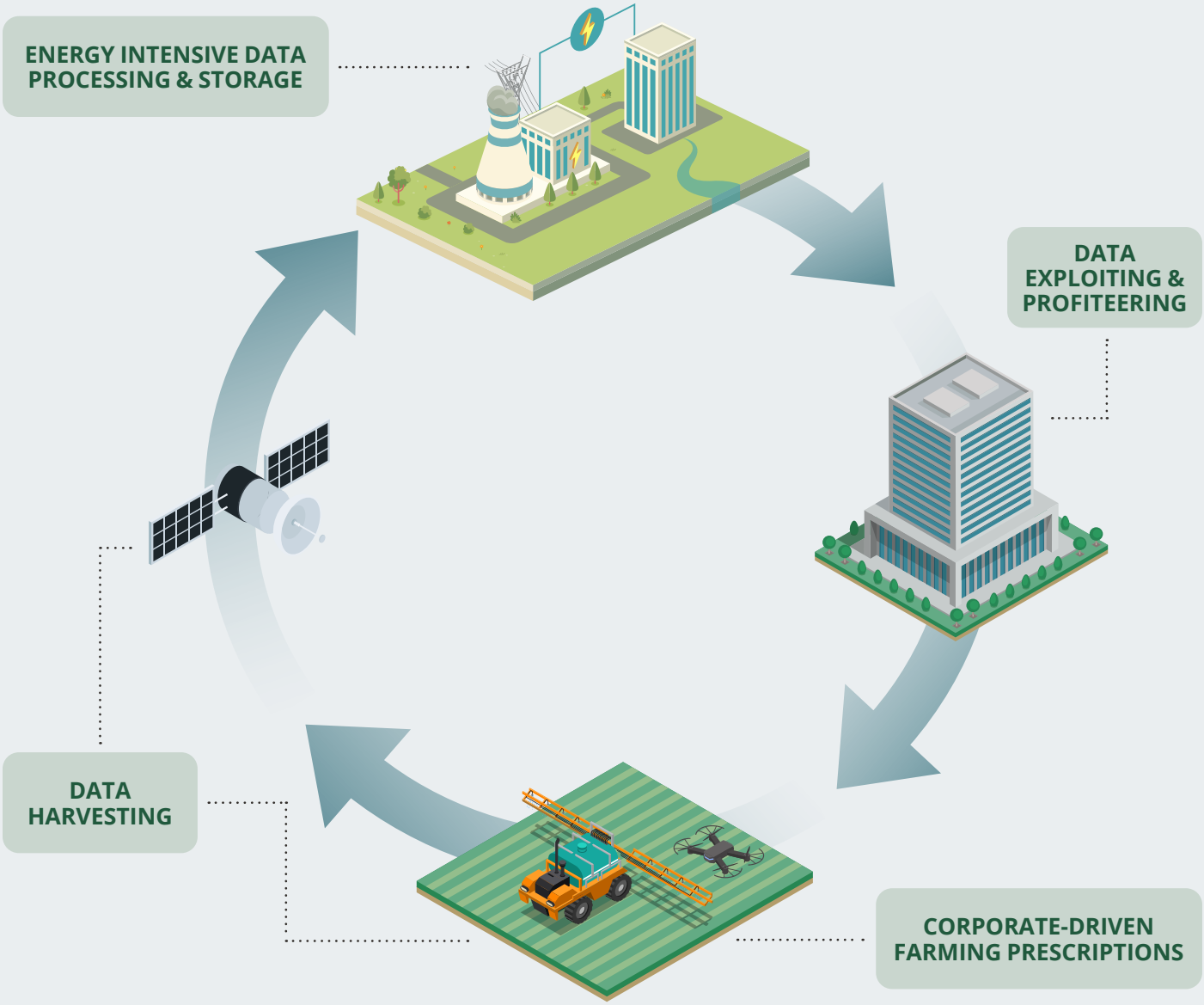
As it stands, however, **today's applications of remote sensing are increasingly shaped by corporate interests and occur in the context of precision agriculture, deepening new and existing inequalities.**[124] Precision agriculture is dominated by major agribusinesses that are changing their business models from supplying inputs (e.g., fertilizers) and farming equipment to offering a wide range of digital services, many of which depend on remote sensing.[125,126]

For over a decade, major agrochemical and machinery companies have been acquiring technology companies to build the hardware and software platforms required to digitalize agriculture (see Figure 3). For example, in 2013, Monsanto (now Bayer) acquired Climate Corporation for close to USD 1 billion and its Climate FieldView platform which tracks crop planting, spraying, and harvesting.[xxviii] In 2018, Agrium merged with PotashCorp to form Nutrien, now the world's largest fertilizer corporation.[127,128] Since then, Nutrien has integrated Echolon into its broader digital platform, Nutrien Ag Solutions, and expanded its services by acquiring the digital agriculture company Agrible for $63 million in 2018, and the wireless data transporter technology Abridge in 2020.[129,130,131]

xxviii This platform gives users access to algorithms based on 30-year historical trends of soil moisture and crop level weather patterns. By plugging in information on different seed crops, farmers receive estimates on their yields for the season. The platform also offers tools for soil analysis, crop monitoring, etc.

FIGURE 3

HOW DATA FLOWS ARE RESTRUCTURING AGRICULTURE



In addition, as precision agriculture depends on vast volumes of complex data (i.e., Big Data for data-driven and automated decision-making), it requires substantial computation power and cloud-based systems to store and process data.[132] As described in our introduction, **big technology companies have entered the agricultural market over the past two decades** to provide digital infrastructure for agribusinesses, public institutions, and startups alike. Alliances between tech giants and agribusinesses have driven major investments in precision agriculture, with the global market valued at USD 11.67 billion in 2024.[133]

Big Tech companies are also developing their own agricultural services to advance digital agriculture. For example, Alibaba offers ET Agriculture Brain, an AI-driven platform for managing crop and livestock farming including real-time animal health and activity monitoring and prescriptions for input use.[134]

Microsoft, Amazon, Alibaba, and Google are also using their power in cloud storage and data-processing tools to develop platforms and software to store and analyze field and weather data in collaboration with major agribusinesses.[xxix] For instance, Microsoft partnered with Bayer to further develop cloud-based data management software and digital tools for Bayer's FieldView platform in 2021. In 2023, data on over 890 million hectares of land was sent to the Climate FieldView app.[135] Nutrien also partners with Amazon Web Services (AWS) to store and process its data.[136]

The push for digital tools within agriculture is actively supported by governments, research institutions, and international organizations, including the FAO. Through their influence, these actors influence which technological pathways are prioritized and which are overlooked in funding, research, and policy. For example, in 2022, the Fertilizer Development Center (IFDC) launched a new Fertilizer and Seed Recommendations Map for West Africa based on remote soil sensing tools.

The web-based platform develops prescriptions "to increase the demand for and use of appropriate fertilizers and improved seed varieties" in the face of climate change.[137] In addition, by converting land and soil into data, remote sensing is being leveraged by both public and private actors to accelerate the growth of carbon credit schemes and biodiversity targets to address climate change.[xxx,138] Yet by identifying land deemed profitable for carbon storage, conservation, or offsetting, or with high biodiversity value, **remote sensing is being used to financialize land and soil.**[xxxi]

Carbon and biodiversity offset markets are driving large-scale land acquisitions or "green grabs", bringing major tracts of agricultural land (most often in the Global South) under the control of some of the world's largest greenhouse gas emitting companies (mostly from the Global North). In recent years, around 20% of large-scale land deals have been driven by carbon offsetting schemes.[139]

xxix In 2020, these four companies collectively accounted for 67% of revenues accruing global cloud infrastructure services. UNCTAD (2021, September 29). Inequalities threaten wider divide as digital economy data flows surge.

xxx Climate-tech companies, including Yard Stick PBC or Agreena, have entered agriculture by pairing remote sensing and AI machine learning to monitor and verify soil carbon levels in support of carbon market schemes. Many public and private carbon schemes also rely on proprietary corporate platforms and precision technologies to function. Farmers enrolled in a company's carbon schemes are often required to use its products (e.g., machinery, software, inputs) to generate or validate carbon credits. For example, Nutrien Ag Solutions or Bayer's Climate FieldView platform bundled their carbon programs with their products and systems. Under these arrangements, providing environmental services effectively locks farmers into a corporate model of agriculture. See Hackfort, S., Marquis, S., & Bronson, K. (2024). Harvesting value: Corporate strategies of data assetization in agriculture and their socio-ecological implications. Big data & society, 11(1), 20539517241234279; see also, IPES-Food. (2024). Land Squeeze: What is driving unprecedented pressures on farmland and what can be done to achieve equitable access to land?

xxxi Here, financialization refers to the increasing dominance of financial actors and market imperatives in the way food is produced, distributed, and consumed. See Hackfort, S., Marquis, S., & Bronson, K. (2024). Harvesting value: Corporate strategies of data assetization in agriculture and their socio-ecological implications. Big data & society, 11(1), 20539517241234279; Duncan, E., Rotz, S., Magnan, A., & Bronson, K. (2022). Disciplining land through data: The role of agricultural technologies in farmland assetisation. Sociologia Ruralis, 62(2), 231-249.

When embedded into precision tools, **remote sensing is also making it easier for investment firms and institutional investors (e.g., pension funds, mutual funds) to monitor field-level data to inform their own investment decisions**.[xxxii] Remote sensing-based tools and opaque algorithms are also being used to digitalize and automate farmers' access to insurance and credit, and to assess agricultural and environmental policy compliance on the basis that these tools will improve efficiency and monitoring costs.[140] For example, satellite images, aerial photographs, and machine learning tools are being used to verify whether farmers meet EU Common Agricultural Policy requirements.[xxxiii] Yet, compliance assessed through these systems does not always reflect environmental outcomes on the ground: many cases of "non-compliance" often arise from policy complexity or misaligned criteria, rather than farmer mismanagement.[141]

Private actors have much to gain from the expansion of digital agriculture. Public digital data is increasingly filtered through and dependent on private infrastructure and technologies. In the EU, for example, the Sentinel-2 mission provides much of the region's agricultural satellite imagery, operated by the European Space Agency.[142] Public agricultural data from Sentinel-2 is accessed through private platforms including Google Cloud and Google Earth Engine, the latter of which now dominates agricultural geospatial and big data analysis.[143]

In the US, global agrochemical giant Syngenta collaborates with Planet Labs, an American public benefit corporation, to provide the satellite imagery and analytics for its digital platform.[144] As the lines blur between what is public and what is private, questions remain around accountability and who governs food systems.

While these dynamics reflect how corporate actors are seeking to drive remote sensing use in agriculture, they represent only one of many possible innovation pathways. Remote sensing technologies are not inherently incompatible with initiatives that strengthen the agency of smallholder farmers, Indigenous Peoples, or local communities. As described above, when priorities are locally defined and remote sensing data is openly accessible, governed as a public good, or embedded within farmer-led or community-controlled knowledge systems, these tools can be part of supporting soil health, land management, and rights over land and resources. However, the ability for these alternative pathways to thrive requires challenging the dominant political and economic structures that continue to concentrate control over digital infrastructure and data collection, processing, and use (See Section 4).

xxxii For example, under the "own-lease out" model, investors lease farmland to independent operators but retain significant influence over farm management decisions. Lease agreements may include the use of certain digital tools or data-sharing agreements that tenant farmers may not always have the power to negotiate, forcing them to relinquish control over the data they generate. See Duncan, E., Rotz, S., Magnan, A., & Bronson, K. (2022). Disciplining land through data: The role of agricultural technologies in farmland assetisation. Sociologia Ruralis, 62(2), 231-249.

xxxiii Research is also being conducted on the use of remote sensing to assess the impact of the EU's Common Agriculture Policy (CAP) greening policies on soil quality. Fugazza, D., Aletti, G., Bertoni, D., & Cavicchioli, D. (2022). Farmland use data and remote sensing for ex-post assessment of CAP environmental performances: An application to soil quality dynamics in Lombardy. Remote Sensing Applications: Society and Environment, 26, 100723.

1.2

Credit: Farmers' Seed Network (China)

MANUAL TOOLS

Farmers have used and developed manual tools and implements to tend soils since the Neolithic period.[145] The first hand tools were crafted from stones and bones, later incorporating wood, bronze, and iron.[146] Despite their ancient origins, manual tools continue to underpin global food production today. They are used for soil preparation, aeration, sowing, weeding, and harvesting – including spades, shovels, hoes, broadforks, rakes, hand or foot ploughs, sticks, and blades.

In this section, we refer to "manual tools" as those powered directly by humans, whether by hand, foot, or physical strength, without the need for motorization or animal traction.[xxxiv]

We focus on manual tools as the majority of farmers worldwide rely on these technologies.

Based on FAO estimates from the early 2000s, less than 2-3% of farmers worldwide use motorized equipment.[147,148] This section invites us to highlight the ongoing relevance of innovation around manual tools, and the social and ecological dimensions of physical soil work often obscured in today's agricultural systems.

xxxiv While we recognize that non-motorized agriculture is often a hybrid of human and animal-powered labour, our analysis here focuses on human-powered tools.

Indeed, **attention to manual tools has decreased significantly since the fossil fuel-powered mechanization of agriculture in the early twentieth century**, when motorized machinery was promoted to replace human and animal labour.[xxxv] Motorization was central to the industrialization of agriculture and food systems. Moreover, by shifting labour from farming to industry, it contributed to the wider transformation of some societies from agrarian to industrial.[149,150]

Animal traction and motorization have shown to increase productivity of labour and land (i.e. increase agricultural production per farm worker and land area), overcome labour bottlenecks and shortages, and increase on- or off-farm household income – depending on factors including levels of indebtedness.[151,152] However, high levels of mechanization have also enabled large-scale monocultures and farmland concentration, and are linked to high capital intensity,[xxxvi] the reduction of agricultural labour requirements, and long-term ecological impacts including removal of farm trees and hedges for tractor access, soil compaction, and erosion.[153,154,155,156]

Regional disparities around mechanization are stark, reflecting different agrarian histories and economic legacies.[xxxvii] **Manual tools remain particularly suited to systems and regions where motorization or animal traction are limited or unsuitable for local conditions**, including small-scale and/or diversified horticulture, swampy terrain, mountainous areas, or terraced hillsides.[157,158,159]

Their use is also high in regions where smallholder, subsistence, peasant, and Indigenous farmers represent the majority of food production – particularly in Asia and Sub-Saharan Africa.[xxxviii] Farming systems that still heavily rely on manual tools also often reflect broader systemic barriers for farmers seeking higher levels of mechanization (e.g., limit access to services, subsidies, and government programs, limited access to land).

As of 2009, Sub-Saharan Africa had one tractor per 1,000 agricultural workers, compared to 11 in East Asia, 21 in South Asia, and 66 in Latin America.[160,161] In many parts of Africa, hoes are the primary agricultural tool for soil preparation.[162] In 2004, a study across 11 African countries found that 84% of farming households had access to hoes, 34% to ploughs, and only 12% to tractors.[163] In contrast, Western Europe, North America, and Oceania are the most highly motorized regions.[xxxix,164]

The use of manual, animal-powered, or motorized tools remains fluid, however, with farmers combining different tools depending on affordability, usability, and relevance.[165] For example, subsistence or smallholder farmers may collectively purchase or rent tractors for land preparation and use manual tools for the rest of their farming activities.[xl,166]

It is also worth noting that data on the use and benefits of manual tools are scarce, reflecting a long-standing bias in research and policy that casts motorization as progress and manual tools as inherently backwards. Many of the examples below rely on case studies and research conducted at the regional, community, or even individual level.

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xxxv Beginning in the 1890s, the tractor marked a major turning point in the motorization of agriculture. From its earliest adoption, critics warned that tractors risked technological lock-in and dependency. Across different world regions, motorization was actively promoted through state policies, development programs, and cheap fossil fuels. It served to reshape labour relations and accelerated farm consolidation. While mechanization reduced certain forms of physical labour, it also reproduced existing class, racial, and colonial hierarchies in the Global North and South, displaced rural workers, increased farmers' indebtedness, and locked many into commercial, fossil fuel-dependent farming systems. For many, tractor adoption remains inaccessible due to high costs, limited maintenance capacity and fuel needs, or lack of unsuitability to local soil conditions. See Clapp, J. (2025). Titans of industrial agriculture: How a few giant corporations came to dominate the farm sector and why it matters. The MIT Press; Pingali, P., Bigot, Y. & Binswanger, H.P. (1987). Agricultural Mechanization and the Evolution of Farming Systems in Sub-Saharan Africa. The World Bank. pp.80-84; Lyubavin, A.N. (1983). On the agricultural machinery industry in Latin America (survey). UNIDO.

xxxvi Here, high-capital intensity refers to heavy investment in and reliance on machinery and equipment with the aim of increasing agricultural productivity. Large farms are often better able to absorb the high fixed costs and credit requirements of machinery.

xxxvii Comprehensive data on mechanization is challenging to obtain, with studies drawing on incomplete or outdated agricultural censuses.

xxxviii Although what is considered small varies by context, farms under 2 ha account for 84% of farms worldwide. Lowder, S. K., Sánchez, M. V., & Bertini, R. (2021). Which farms feed the world and has farmland become more concentrated?. World Development, 142, 105455.

xxxix Canada has about 19 tractors per 1,000 ha of arable land, the United States 27, Australia 22 and Europe 34, with each tractor typically operating large areas. FAO. (2022). The State of Food and Agriculture 2022. Chapter 2 & Annex 2.

xl In India, for example, where up to 90% of land preparation is done by tractor, farmers also rely on manual tools for planting, weeding, and harvesting. Bhattarai, M., Singh, G., Takeshima, H. & Shekhawat, R. (2020). Farm machinery use and the agricultural machinery industries in India. In An evolving paradigm of agricultural mechanization development: How much can Africa learn from Asia? IFPRI.

Impacts on soil health

A wide variety of practices to support soil health can be carried out using mechanization, including manual tools, animal traction, or machinery. None of these are inherently beneficial or harmful, as outcomes depend on context and how they are integrated within a specific farming system. For example, heavy tractor use can lead to soil compaction,[xli] just as intensive hoeing or steel and iron ploughs have been shown to degrade soils and drive erosion.[167,168] At the same time, the current scale and speed of land degradation could not exist without the motorization of agriculture and large-scale intensive farming practices.

Manual tools have long been integral to complex soil management and innovative soil health practices.[169] **A number of studies demonstrate how manual tools and animal traction are used to support sustainable soil management, particularly in small-scale and Indigenous farming systems that rely on multiple, integrated practices.**[170] In particular, manual tools adapted to local environments can support soil restoration, improved soil structure, and water retention.

For example, in semi-arid regions, farmers construct soil bunds and zaï pits with hoes and spades to restore degraded land and improve water infiltration. In Oltukai village in Tanzania, MVIWAARUSHA, a local network of farmer and pastoralist groups, is supporting a community-led project to restore 150 acres of pasture using these methods.[171,172] Zaï tillage systems and use of on the manga hoe (or hand hoe) has improved water retention and soil quality, boosting sorghum and cowpea yields.[173] In the Indian Himalayas, the Apatani people have used digging sticks, seed dibblers, and other manual tools for centuries to support agroforestry systems and crop rotation to nourish local soils.[174]

In Egypt's Sinai Peninsula, the Habiba community uses rakes and grub hoes in combination with local seeds and adapted irrigation systems to restore soils and grow food for the local community.[175] Through relationships built for the past 30 years with local Bedouin families and with the support of local and national research centers, Habiba community has developed innovative practices to work with the harsh conditions of the desert to foster thriving agroecosystems and healthy soils. They have now become a key site in the region for knowledge-sharing and learning about, and experimenting with, desert regeneration.

Landscape engineering, including the creation of terraces and contouring, has also heavily relied on innovations made and adapted from centuries ago. In Nishi-Awa, Japan, farmers practice steep-slope agriculture by using the sarae (an inclined hoe designed for sloped terrain) for soil preparation, terrace construction, and a mulching practice known as *Kaya* (grass to lay), which collectively help minimize soil erosion.[176,177] In the Andes, the pre-Hispanic agriculture system known as Waru Waru has been revived since the 1990s to adapt to climate change.[178] This innovation involves cultivating native species in floodplains on manually constructed raised fields (e.g., using the Andean footplough),[179] interwoven with irrigation channels to help reduce risks of frosting and increase soil fertility.[180]

In general, practices such as intercropping, cover cropping, crop rotation, manure application and composting, have been shown to increase soil microbiome, improve soil structure, and enhance soil multifunctionality (e.g., nutrient recycling).[181,182,183] These practices can be supported by many forms of mechanization when accessible.[184] Yet they are most often implemented using manual tools, particularly in diversified and small-scale farming systems.

For example, the Machobane farming system in Lesotho relies on manual tools to manage intercropping, rotations, and organic fertilization.[185] In the Assam region of India, the Bodos draw on traditional knowledge and use locally crafted manual tools, such as the *kodhal* (digging hoe), *grandi/dangan* (large hammer), and danger (rake), to work the soil and incorporate organic biomass (e.g., cow dung, plant materials) into highly diverse cropping systems.[186,187,188] In Uganda, banana farmers use hoes, spades, pangas (machetes), and wheelbarrows to dig and maintain planting pits enriched with organic materials, creating long-term nutrient reservoirs between banana stems.[189]

xli Soil compaction due to tractor use is caused by the weight of the tractor, the number of times it passes over the soil, and soil type. Limiting tractor passages can already greatly reduce compaction. See example, FAO (2022). Agricultural mechanization and sustainable agrifood system transformation in the Global South. Background paper for The State of Food and Agriculture 2022.

Impacts on gender, labour, and livelihoods

While manual tools can support a close connection to the land and soil, the physical labour and time required to use them is significant relative to more mechanized systems. One study estimated that farming with manual tools allows a single worker to farm 1 hectare of land, producing between 1 to 10 tonnes of grains, compared to motorized systems, that could enable the same worker to cultivate up to 100 times more land and produce 100-1,000 times more grain.[190] Low labour productivity associated with manual tool use can therefore undermine farmers' livelihoods, by limiting the volume of crops they can produce or by reducing the time available for additional on- and off-farm activities (e.g., value addition of on-farm products, seeking additional wage labour).[xlii]

Repetitive tasks, long working hours, and heavy loads can also lead to injury and strain on large and small farms alike – risks worsened by factors including a lack of safe working conditions, rest, nutrition, or access to adequate healthcare.[191] Whether manual tools contribute to dignified work or exploitation also rests on broader structures, including social norms, gender relations, labour rights, or access to land.

For example, in many regions, **women are the primary users of manual tools because they face persistent barriers to access other agricultural tools** (including digital and motorized tools), education, land, and finance compared to men.[192]

Gender biases in agricultural policies and social norms remain in many regions, even though women represent almost 40% of the global agricultural workforce[193] – often working as unpaid agricultural labourers, self-employed producers, or on- and off-farm seasonal workers.[xliii,xliv,194]

Technologies both reflect and shape these gendered dynamics, often with deep historical roots. In regions where hoe-based farming predominates to weed and prepare soils, women have remained central to agricultural work, in part because these activities can be paused and resumed to accommodate care work.[xlv,195,196] By contrast, plough-based and motorized agriculture tend to require access to capital, and uninterrupted time, often to the exclusion of women.[xlvi] Studies from Lesotho, Kinnaur (India), and France illustrate these historical patterns, where women are the primary users of hand hoes, and men dominate the use of ploughs, ox-drawn equipment, and motorized machinery.[197,198,199]

Indeed, **while motorization can reduce physical strain, it has had mixed impacts on women farmers and farmworkers.** A cross-country study in Ethiopia, Nigeria, Tanzania, Ghana, Nepal, Vietnam, southern India, and southern Tajikistan found that the use of tractors or harvesters pushed more women into non-farm work than men – improving their incomes in some circumstances, but driving others into less productive and more precarious activities.[200] In Norway, motorization has been a main contributor in excluding women from farming, due to assumed gender roles and competencies.[201] In India, a 10% increase in motorized tilling between 1999 and 2011 reduced women's farm labour by 5%, coupled with the absence of off-farm work opportunities.[202]

xlii These trade-offs are also shaped by multiple factors including market integration, indebtedness, and the availability and cost of labour.

xliii In some regions, rural male outmigration and a high burden of care work often make it difficult for women to support their livelihoods. Rural male outmigration is common across the world but is particularly high in parts of Southern and Central Asia, Latin America, and the Caribbean. See FAO. (2023). The status of women in agrifood systems and FAO. (2025). Bringing women innovators to the fore: Engaging in gender-responsive, farmer-led innovation and research.

xliv Despite international frameworks including the 1997 Convention on the Elimination of All Forms of Discrimination against Women or the Right of rural women to access appropriate technology (Article 4), agricultural technology development is rarely developed with gendered/gender-sensitive approaches. OHCHR. Convention on the Elimination of All Forms of Discrimination against Women New York, 18 December 1979.

xlv Other examples of gender disparities in tool development include the introduction of rice mills in Bangladesh, replacing female labourers previously engaged in winnowing, threshing, and hand-pounding rice. In Indonesia, motorized rice hullers caused 1.2 million landless women to lose their jobs, reducing total income for female farm workers who did not own land and widening inequalities between landowners and laborers. See FAO. Women and the green revolution. Accessed August 20, 2025.; Farnworth, C. R. et al. (2020). How Will Mechanizing Mung Bean Harvesting Affect Women Hired Laborers in Myanmar and Bangladesh? Sustainability, 12(19), 7870. https://doi.org/10.3390/su12197870.; Gunawan, M. C., & Fakhruddin, F. (2019). Does Technology Influence Female Farmer Income? Case Study in Pidie District, Aceh. In 1st Aceh Global Conference (AGC 2018) (pp. 539-543). Atlantis Press.

xlvi In certain regional and historical contexts, motorized equipment has enabled greater participation of and reduced physical labour for women (e.g., during World Wars 1 and 2 in North America). See for example, Jellison, K. (1993). Entitled to power: Farm women and technology, 1913-1963. University of North Carolina Press.

Furthermore, time-saving and labour-reducing technologies can take multiple forms. **When designed with or by farmers, manual tool innovation can be better adapted to different cropping systems and local contexts, and has been shown to make soil management tasks faster and safer, reduce physical strain and injury, and improve quality of life.** For example, many manual tools are designed around male body proportions, with women farmers experiencing physical strain after their use.[xlvii,203] In Maharashtra, India, women farmers have redesigned hand tools better adapted to their activities, including an improved sowing tool, *davra* (cycle weeder), and *haat davra* (hand-held weeder) that reduce physical labour and reliance on hired labour.[204] In Greece, Tzoumakers' open lab developed an ergonomic hand-digger for small-scale horticulture, allowing easier and more precise work than the standard fork.[205] In Western Kenya, a study centered on human-centered design[xlviii] brought researchers and farmers together to prototype and evaluate new, more ergonomic hand tools for soil preparation, cropping, and weeding.[206]

Community-based labour systems are also crucial social innovations that enable more dignified livelihoods, supporting skill and knowledge sharing and improving community autonomy. In some small-scale agroecological systems, labour is shared across households, and organized through different notions around community, reciprocity, and time (e.g., working with natural processes).[207] **Community farming, cooperatives, work brigades, and mutual aid networks help share labour responsibilities.** Some farmers and farmworkers describe this collective labour and more diverse tasks as fostering well-being and meaning in their work.[208]

A first step in supporting these types of social innovation systems is countering the notion that manual labour is inherently "drudgerous", a narrative that reinforces agricultural motorization and automation as the only pathways to progress. Indeed, drudgery can exist in both manual and more mechanized farming systems, defined as repetitive, physically and/or mentally draining work, often lacking in autonomy.[xlix,209]

Manual tools can also be part of exploitative agricultural systems. Many large industrial farms rely on manual migrant labourers, and have been described as "factories in the field."[l,li] Additionally, several labour- and time-demanding tasks in agroecological production, such as compost preparation or manure collection, are often carried out by women, which can reinforce existing gendered divisions of labour.[210] **A central question, therefore, is not whether to replace manual labour with higher mechanization and automation, but how to ensure healthy and dignified agricultural work and fair incomes**, particularly in a global context of aging rural populations and potential labour shortages.[lii]

xlvii Evidence suggests that women can face greater challenges in hiring and supervising labourers due to existing socio-cultural structures. FAO. (2023). The status of women in agrifood systems.

xlviii Human-centered design is a research method based on understanding users' needs, and includes co-developing, prototyping, and evaluating tools with those users.

xlix Small-scale and agroecological farms do not provide better working conditions by default and may depend on unpaid or volunteer labour and involve highly intensive or self-exploitative work (e.g., by family or community members). See Bezner Kerr, R. et al. (2022). Human and social values in agroecology: A review. Elem Sci Anth, 10(1), 00090.

l For more on labour and migration in food systems, see IPES-Food's upcoming report (June 2026).

li In large-scale Californian monocultures in the 1950s-60s, employers required migrant workers to use short-handled hoes to work quickly while limiting disturbance of delicate crops (e.g., beets and lettuce). The hoe caused workers chronic pain, forcing them to stoop up to 12 hours a day in the fields, until it was banned in 1975 following a campaign by the United Farm Workers labour union. See Cozzens, T. (2015). Defeating the Devil's Arm: The Victory over the Short-Handled Hoe in California Agriculture. Agricultural History, 89(4), 494–512. See also, Espinosa, G., Elizondo, V. P., & Miranda, J. (Eds.). (2005). Latino religions and civic activism in the United States. Oxford University Press, USA. p.106.

lii While complex, labour shortages arise from an aging rural population and farming outmigration due to low wages and working conditions, lack of access to land and capital, greater reliance on automated technologies, lack of government incentives to provide meaningful rural employment, and increasingly climate change. See Mizik, T. et al. (2025). Challenges of employment in the agrifood sector of developing countries—a systematic literature review. Humanit Soc Sci Commun 12, 62.

Impacts on autonomy, knowledge, and control

Many manual tools carry long-standing cultural and spiritual significance as part of broader social heritages, from the Andean *chaquitaclla* (foot plough) to the Malagasy *angady*, a versatile spade with a long handle used for plowing, planting, weeding, ridging, harvesting, and land leveling.[211] In Madagascar, for example, only 0.02% of farms work with machinery and many rely on the *angady*.[212,213] The tool symbolizes ancestral heritage, Malagasy peasant identity, and mirrors farmers' relationship to land, traditions, and societal values – to some, even representing resistance to modernization.[214]

Innovation around manual tools is often supported through local knowledge exchange, collective brainstorming, and open-source design. Hundreds of variations of manual tools have emerged around the world over time, each adapted to specific agricultural tasks, and regional and cultural contexts. As smallholder farmers and rural communities make up a large share of the world's poorest populations,[liii] manual tools are essential to their livelihoods, allowing farmers to keep costs low while retaining autonomy from costly machinery, energy, and input providers.[215] Unlike other tools, they can be used regardless of power or infrastructure outages, making them resilient in contexts of instability or when support from public services is weak. This is particularly important as many farmers face high levels of indebtedness.[liv]

While some manual tools are manufactured by state-owned or private companies,[216] **many tools continue to be made, modified, and repaired by blacksmiths, welders, and other artisans within local communities who carry the knowledge, skills, and cultural heritage to maintain them.** These skills can sustain employment and value in local communities, where job opportunities often remain limited and where out-migration is high.

Across Asia and Africa, many tools are made from locally sourced materials by village artisans, small community workshops, or Indigenous communities preserving artisanal knowledge and skills.[217,218,219,220]

In the US, the Community Alliance with Family Farmers highlights that manufacturing of small-farm equipment all but disappeared in the country since the 1970s and works to support both farm-driven digital and manual tools, closely developed with engineers, designers, and tradespeople.[221] In Belgium, Fabriek Paysanne, a non-profit aimed at supporting peasant farmers, trains farmers in metalwork and mechanics, co-designs tools, and hosts workshops on tool repair.[222]

At the international level, the Grassroots Innovations Assembly for Agroecology (GIAA) hosted by Schola Campesina aims to value and promote grassroots innovation systems by bringing together organisations worldwide supporting local innovations, maintaining an open-source online platform documenting tools and technologies developed or promoted by grassroots organizations, including manual tools.[223] (See Box 7.)

Credit: CTA ACP-EU

liii Recent estimates suggest that 80% of those living in extreme poverty worldwide are in rural areas and rely largely on agriculture for their livelihoods, mainly as smallholder farmers and farmworkers. UN. (2023). Eradicating rural poverty to implement the 2030 Agenda for Sustainable Development. Report of the Secretary-General. A/78/238.

liv Agricultural work is associated with both physical and mental health risks, including high levels of stress, depression, anxiety and suicide. Many factors affect the mental health of farmers and farmworkers related, including indebtedness, isolation, and concerns over climate change. See Daghagh Yazd, S., Wheeler, S. A., & Zuo, A. (2019). Key Risk Factors Affecting Farmers' Mental Health: A Systematic Review. International Journal of Environmental Research and Public Health, 16(23), 4849.; King, E. et al. (2023). Engaging the agricultural community in the development of mental health interventions: a qualitative research study.; Saju, S. et al. (2024). Farmer's mental health and well-being: Qualitative findings on protective factors. Journal of neurosciences in rural practice, 15(2), 307–312.

BOX 7

TOOLS AND MACHINERY DESIGNED TO ADDRESS FARMERS' NEEDS

Many farmer-led innovation initiatives work on designing, developing, or adapting manual, motorized, and digital tools to meet farmers' needs, some examples include:

- In **Brazil**, the Landless Workers' Movement (MST) has partnered with a Chinese company to develop machinery suited to peasant family farming. The collaboration includes trials to test and adapt machinery to the local context and plans to build three mechanization factories and a bio-input facility in the Northeast of Brazil to counter market concentration and expand access to appropriate technologies for family farmers.[224]
- In **France**, l'Atelier Paysan, a cooperative supporting peasants' technological sovereignty, has developed a range of tools, including a hitch triangle that allows implements to be attached to a tractor within seconds while the operator remains in the driver's seat.[225] This improves ergonomics, saves time, and reduces the risk of accidents such as getting caught between the implement and the tractor. The network has also designed an improved wheel hoe (or push hoe), providing a faster, ergonomic, and lightweight tool for tilling and weeding.[226]
- In **India**, Mittidhan Dharampur, a social enterprise for the collective design and production of farm tools, has developed a multi-functional wheeled weeder usable for land preparation, planting, and weeding.[227] The organization is also aiming to reduce the travel time for farmers to acquire tools that are easy to maintain, as many travel to markets up to 30-40km away only to have access to a limited or outdated selection of tools.[228]
- In **the US**, Semillero de Ideas – a non-profit supporting farmworker-led innovations to improve working conditions and challenge the structural racism of industrial agriculture[229,230] – organizes annual challenges to encourage farmer-driven innovation. In 2023, the top prize went to a farmworker for an innovative padded harness attached to a harvesting bucket, designed to provide more comfort and back support while picking and carrying cherries. The organization also runs workshops on how a diversity of tools (digital, human-powered, etc.) can better support farm workers.
- **Online**, FarmHack is a farmer-driven open-source community and platform that develops and shares affordable, adaptable, and repairable tools for resilient agriculture. These tools are highly diverse, including hand tools, implements, composting bins and digital tools. One example of manual tool shared on their platform is a wheel hoe built from bike parts.[231]

Many organizations also drive social innovations, such as collectivizing machinery through cooperatives or adopting open-pricing systems based on ability to pay, in order to enhance technological accessibility.

Credit: l'Atelier Paysan

Implications for power in food systems

From the lens of science and technology studies (STS), tools and technologies are best understood by what they enable, constrain, and make possible (i.e., "affordances").[232] Large-scale motorization has influenced who performs soil work and under what conditions. It has been a symbol of agricultural modernity and universal progress from its earliest days.[233] Crops and fields have been redesigned and standardized to accommodate the use of machinery.

It is important to acknowledge the practical benefits brought about by higher levels of mechanization, including reducing arduous labour, saving time on certain farming activities (e.g., faster sowing and harvesting essential for short crop windows), or supporting crop yields in some contexts.[234] Yet, motorization has not always delivered equitable or sustainable outcomes. It has contributed to land consolidation and soil degradation, the marginalization of peasants and farmworkers, and failure to increase farming incomes.[235] **Each new wave of large-scale technological development has further sidelined small-scale, diversified farmers – or pushed them out of farming altogether.**

Meanwhile, manual tools have been cast as symbols of poverty and underdevelopment.[lv] "Drudgery" has frequently been invoked to justify agricultural modernization in a way that marginalizes and undervalues farmworkers, women, and the physical and intellectual labour of farming. Yet smallholder systems (under 2 hectares) which rely mostly on manual tools make up 84% of the 608 million global farms today,[236] and are, on average, associated with higher levels of biodiversity and crop diversity than larger farms.[237]

Despite their relative 'simplicity', manual tool innovation allows these farmers to retain their agency and livelihoods.

They offer flexibility, adaptability, and collective learning in ways that standardized and complex tools often do not.

They also help to highlight questions on how agricultural work can be shared, recognized, and dignified. Ivan Illich refers to "tools of conviviality" as those that allow users to exercise autonomy and creativity, contrasting them with industrial tools that diminish these qualities and assume that technology must be capital-intensive, proprietary, and labour-replacing to be valuable.[238]

The aim here is not to romanticize physical labour nor is it to reject high levels of mechanization outright. Instead, it is about asking how to build farming systems where manual work is safe, valued, and supported. Indigenous communities, women's farming cooperatives, farmer-led workshops, and open-source labs are already reclaiming technical skills, prioritizing repairability over obsolescence, and dignity over exploitation. With little to no public policy support, they are also making visible the labour and expertise involved in upholding agricultural systems – particularly of women, Indigenous Peoples, farmworkers, and a broader set of local actors (e.g., artisans, mechanics, blacksmiths).

Manual tools also offer important possibilities in a context of climate change and increasing resource scarcity. Locally crafted, low-energy, and repairable technologies can ensure a degree of resilience amidst rising energy prices and volatile input markets. Yet, many of these same tools and the agricultural practices they support are at risk of extinction. In this context, innovation plays a crucial role in ensuring that the most relevant tools remain available and accessible to those who need them. It is also about ensuring agency and farmers' adaptive capacity remain at the center of technological choice, whether manual, animal-tracked, motorized, or digital.[239,240]

lv For example, while aimed at reducing the strain and drudgery of women's agricultural labour, the African Union's "Retiring the Hoe to the Museum" statue in Burkina Faso symbolically captures the policy imperative to replace hand tools with motorized equipment. See FAO and AUC (2019). Sustainable agricultural mechanization: A framework for Africa – Synopsis. Addis Ababa and African Union (2019, 21 October). African Union Unveils a statue "Retiring the Hoe to the Museum" to Launch a Continental Agenda to Improve Agriculture Mechanization among Women Farmers.

2

INNOVATIONS TO PROTECT CROPS FROM PESTS AND DISEASE

Today, an array of solutions is being put forward to manage pests and diseases in crop production, with many aiming to reduce chemical input use. This section explores two distinct innovations: precision spraying technologies and ecological pest management (EPM). While the former is largely embedded in systems reliant on external inputs, EPM approaches aim to strengthen functional agrobiodiversity through system redesign. Below, we assess how these pathways impact input use and ecological resilience, farmer and farmworker health and labour, on-farm decision-making, knowledge systems, and dependency and power dynamics in food systems.

Protecting crops from pests and diseases is crucial to agriculture and ensuring the food security and livelihoods of millions. The increasing frequency and severity of plant diseases and pests not only poses significant risk to food production, but also to on- and off-farm biodiversity, soil health, and the nutritional quality of crops.[241] Climate change is creating more favourable conditions for pests and pathogens to thrive, through warmer temperatures, unpredictable weather patterns, and more extreme weather events.[242] At the same time, industrial monocultures increase the vulnerability of entire fields to outbreaks – with globalized trade facilitating the potential for the rapid spread of pests and diseases.

A wide range of crop diseases and pests threaten agricultural production, including weeds, insects, viruses, fungi, and bacteria. **Every year, 20-40% of global agricultural production is lost to pests and diseases on the field**, with significant variations depending on context and crop type.[243] In 2019, 30% of global rice crops, 21-22% of wheat, corn, and soybeans, and 17.2% of potato crops were lost due to pathogens and pests.[244] The estimated annual global cost of plant disease is around USD 220 billion and around USD 70 billion for invasive insects.[245]

Farmers rely on a range of methods to ensure crop health, depending on farming systems, farm size, and available resources. These include agricultural practices (e.g., push-pull method, crop rotation, cover cropping) to improve pest and disease resistance.

Crops can also be protected through a range of manual tools or automated technologies (e.g., mechanical weeders, sprayers), biological control (i.e., use of beneficial insects or microbes, conservation methods, biopesticides), physical barriers (e.g., row cover, protective netting), or plant breeding techniques (e.g., disease- or pest-resistant varieties developed through traditional breeding or genetic engineering). To complement these strategies, tools and practices also exist to monitor crop health, through inspection, testing, or digital methods.

Despite this wide range of options, **synthetic pesticide use** – in other words, the use of chemical insecticides, fungicides, and herbicides – **has become a dominant crop protection strategy around the world.** Expanding dramatically after WWII, the use of synthetic farming inputs built on advances in chemical research and the repurposing of chemical plants in the post-war period. The adoption of agrochemicals was heavily promoted by the United States and Western European countries, through government policies encouraging their use as a means to boost food production and stabilize post-war economies.[246,247] In addition, companies like Monsanto, Bayer, and Dow Chemical – all of whom had produced wartime chemicals[248,249] – played a key role in fueling input-intensive farming through their growing influence over research, agricultural extension services, and policy-making.[250]

Global annual pesticide use has only increased since – doubling between 1990 and 2022 to reach approximately 3.7 million tonnes.[251] Over the past decade, pesticide use has also grown by 153% in low-income countries, far outpacing the global average increase of approximately 20%.[252] Pesticide resistance has also developed alongside this growth,[lvi] with more than 16,000 documented cases of insecticide resistance involving more than 600 pest species in recent years.[253] As a result, many farmers have had to apply pesticides more frequently and in higher doses, and rely on a wider number of agrochemical products to combat new or worsening pests and disease.[254]

lvi The first study on pesticide resistance was published in 1914. See, A. L. Melander. (1914). Can Insects Become Resistant to Sprays?. Journal of Economic Entomology, Volume 7, Issue 2, 1. pp 167–173.

Pesticides are among the most toxic substances in the world and their overuse has led to major detrimental effects on the environment, human health, and livelihoods.[255] Their use contaminates water, soil, and air – with groundwater contamination found up to 1,000 kilometers away from the location of their application.[256,257,258] They are also a primary driver of biodiversity loss, disrupting soil microorganisms, insects, pollination, and much more.[259]

Chronic exposure to pesticides can lead to a range of public health threats, particularly for farm and food workers, including respiratory issues, neurological disorders, cancer, and negative impacts on reproductive health.[260]

Pesticide residues in food are also a health concern as studies show that long-term exposure can increase risk of endocrine disruption, reproductive problems, neurodegenerative diseases (e.g., Parkinson's and Alzheimer's), and certain cancers.[261]

Studies have also revealed the major societal costs of pesticide usage.[262] For example, a 2021 study by Le Basic showed that EU taxpayers paid approximately EUR 2.3 billion for costs directly related to pesticide use in 2017 (e.g., treatment of drinking water, occupational health impacts, GHG emissions) and an additional EUR 105.9 billion in indirect costs (e.g., developing countermeasures to protect biodiversity, public aid for agriculture).[263] Together, these costs add up to more than twice the annual profits of the pesticide industry.[264]

2.1

PRECISION SPRAYING TECHNOLOGIES

Precision spraying technologies are designed to collect and analyze data to apply agrochemicals in the right quantity, exactly where and when they are needed. They are often promoted for their ability to "de-risk" agrochemical usage by controlling variability and replacing potential human errors or environmental uncertainties with data-driven decision-making.

Since the 1990s, precision spraying technologies have advanced exponentially, encompassing a wide range of tools, including drones, helicopters, planes, tractors, or robotic sprayers all equipped with a combination of advanced sensors, GPS-guided systems, and AI computing.[lvii] As mentioned in Section 1, uptake of precision tools is growing fastest on large-scale, row-crop, monocultures most reliant on agrochemical input use.[265,266] In the US, over 50% of corn, cotton, rice, sorghum, soybeans, and winter wheat production uses precision technologies in some way.[267]

In 2019, Variable Rate Technologies (VRT) were being used on 31% of cereal farms in England and 15% of farms in Australia.[268]

Initially developed and used for military purposes, drones are increasingly being adapted and produced for agricultural applications and are one of the main emerging mediums for precision spraying.[269] Both manually controlled and automated drone sprayers are most widely used in East Asia, largely due to regulatory support and their relevance to farming regions with challenging terrain, such as the steep hillsides of paddy fields. In 2021, China used over 120,000 drones to spray more than 70 million hectares of farmland,[270] covering 64% of its arable land.[271] In the same year, Japan used precision drones to spray 1 million hectares – about 20% of its arable land.[272]

lvii Depending on the system used, precision spraying tools can be automated, semi-automated, or manned systems equipped with advanced GPS guidance or sensors. Machinery can be equipped with a variety of spraying systems, including spot spraying, electrostatic spraying, or variable-rate spraying systems.

At the same time, precision spraying tools are increasingly being designed and marketed for smaller-scale farmers and more diverse agricultural systems.[273] For example, XAG, a Chinese company specializing in precision spraying drones in collaboration with Alibaba Cloud,[274] promotes its technology for all farm sizes and terrains.[lviii] Though investments are still comparatively marginal, low-cost robotic sprayers for small-scale farms are also being developed by a number of agritech companies and research institutions, including a consortium of Malaysian agricultural research institutions.[275]

As discussed in Section 1, digital agriculture, including precision spraying, is driven by a handful of agribusinesses and tech companies, **and only a handful of multinational corporations control the majority of the global agrochemical market today.** In 2023, the leading 4 agrochemical companies controlled 61% of the global pesticide market,[276] equivalent to over USD 62 billion in sales.[277] In parallel, high levels of market concentration are pervasive in the agricultural machinery industry, where the top six companies control half of the global market and are working rapidly to develop precision technologies to expand their market shares.[lix,278]

Impacts on pesticide use

Precision spraying tools for pest and disease protection are most often promoted for their capacity to reduce pesticide use, improving environmental sustainability and human and environmental health outcomes. Industry claims are ambitious in this regard, suggesting that these technologies could reduce pesticide use by up to 90%.[279] **Precision spraying does appear to reduce pesticide use per hectare in certain contexts.** However, studies vary greatly in their assessments, with estimates ranging from 5-80% reduction per hectare compared to conventional spraying methods.[lx,280] It is also worth noting that data supporting industry claims can sometimes be opaque. For example, a 2021 study by the Association of Equipment Manufacturers and the pesticide lobby group CropLife claims that precision agriculture resulted in reduced pesticide use, yet the data supporting the study is not publicly available.[281] Overall, the degree of pesticide reduction depends on a complex interplay among a range of factors, including crop variety, weed density, field characteristics, and weather conditions. The impacts of precision spraying technologies also vary significantly by region, farm size, and cropping system. In particular, reduction in pesticide use tends to be more pronounced during earlier stages of crop development, when leaf area is limited and foliage cover between rows is minimal.[282] Similarly, pesticide precision spraying technologies are most effective when weed density is low, requiring less pesticide use.[283,284]

In addition, **conventional precision spraying technologies currently target a very limited number of staple commodity crops.** For example, John Deere's See & Spray Premium Precision Sprayer specifically targets weed control for corn, soybean, and cotton. Similarly, Bosch and BASF's joint venture, One Smart Spray,[285] is only designed for corn, soy, cotton, sunflower, canola, and sugar beet crops.[286] The logic may be that focusing on the most widely cultivated crops offers the greatest pesticide reductions, but it risks reinforcing that precision spraying technologies are designed first and foremost to serve and maintain large-scale, export-oriented commodity production systems. In addition, precision spraying operates within a pesticide-centric paradigm to manage pests and diseases. By ignoring issues related to pesticide resistance, for example, it risks perpetuating a technological treadmill of new tools to continuously mitigate the accumulating impacts of pesticide use.

However, precision spraying technologies do not exclusively rely on agrochemical use and could be applied to biopesticide use, but studies and trials remain limited.[lxi] Only two documented cases were identified in this regard: a pilot trial conducted by the Centre for Agriculture and Bioscience International using precision spraying drones against the desert locust in Kenya, and a European Union-funded biopesticide spraying robot first trialed in Norway.[287,288]

lviii The company is now expanding in countries like Vietnam and Japan (the latter in collaboration with Bayer) on the basis that more complex terrain and small farm sizes could benefit from drone usage. XAG. (2018, November 21). Bayer and XAG Deepen Collaboration in Agricultural UAS Application in Japan; Bot & Drone News Asia Pacific. (2022, July 7). XAG P100 Agricultural Drone Debuts in Vietnam.

lix Leading companies, Deere & Company, Kubota, CNH Industrial, AGCO, CLAAS, and Mahindra & Mahindra, control 49.8% of the agricultural machinery market. From ETC Group. (2022). Food Barons 2022: Crisis Profiteering, Digitalization and Shifting Power.

lx It is worth noting that studies evaluating the impacts of precision spraying do so relative to conventional spraying methods, rather than to alternative methods for pest and disease control.

lxi Biopesticides are pest management products primarily derived from natural sources, including bacteria, fungi, viruses, plants and minerals. Some biopesticides are gene-edited, carrying their own risks (e.g., unintended effects on non-target organisms, ecological imbalances, proprietary inputs). (For more on gene editing see Section 3.1.)

Impacts on farmer and farmworker health

Evidence suggests that precision spraying likely reduces farmers and farmer workers' pesticide exposure.[lxii] Farmers and farmworkers remain most vulnerable to high pesticide exposure during the spraying process.[289] Autonomous systems such as robotic sprayers significantly reduce human physical involvement during pesticide application, thereby limiting direct exposure.[290,291]

Proponents of precision spraying also claim that these technologies are specifically designed to minimize drift, reducing the risk of human and environmental exposure more broadly.[292] For example, a Swiss study demonstrated that drift levels from precision spraying fall within regulatory limits.[293] In Australian sugarcane fields, herbicide runoff was found to be 39% to 54% lower with the use of automated robot sprayers, compared to traditional broadcast spraying.[294] Nevertheless, high exposure risks remain during other tasks, including preparing and cleaning spraying equipment, where precision technologies provide little to no protective advantage.[295] Activities like planting, weeding, thinning, or harvesting involve less pronounced but ongoing exposure to pesticides,[296] which precision technologies do not necessarily address.

As stated above, pesticide residues in food are a reality across the globe. While precision spraying offers some improvements over conventional spraying methods, it does not eliminate the well-documented pesticide threats to farmers and farmworkers, nor for environmental and public health. Ultimately, **the use of pesticide precision spraying – and the regulatory frameworks that underpin their use – still operate under the assumption that some degree of exposure is inevitable within agriculture.** By reinforcing a logic of ongoing dependence on chemical inputs, this assumption sidelines alternatives that could eliminate or more significantly reduce the use of pesticides altogether.

Impacts on labour and livelihoods

In the analysis that follows, we focus on the labour impacts of precision spraying machinery that relies on (largely automated) data-driven decision-making, rather than on the impacts of mechanization and manually controlled machinery more broadly (e.g., drones or tractors). (See Section 1.2 for more on manual and motorized tools.)

Precision spraying is promoted as a means to reduce time spent on input application and alleviate labour requirements, especially in countries facing aging farming populations, farm succession challenges, and labour shortages.[297,298] Compared to conventional spraying methods (e.g., tractor spraying, backpack spraying), precision technologies do appear to reduce the intensity and drudgery of certain physical tasks, particularly for farmworkers.

Manually controlled or automated, drones can cover large areas quickly, and potentially replace the drudgery of farmers and farmworkers spent on manual spraying. However, in already highly mechanized systems, **the shift to automated precision spraying may not significantly reduce physical drudgery, but have more significant impacts on time efficiency.** For example, one study estimated that automation could save USD 1.5 billion across US corn farms on the basis that a single worker could oversee a greater number of machines, increasing time efficiency and per worker productivity.[299] A 27-32% time saving was demonstrated in small- and medium-scale apple orchards in the USA, translating into a 28% reduction in labour to operate automated spraying machinery compared to conventional methods.[300]

lxii In one study, the highest levels of dermal exposure to pesticides were found on manual sprayers workers (compared to other farm workers handling pesticides, e.g., for mixing of loading). This suggests exposure is highest in those directly applying pesticides in the field. Tudi, M. et al. (2022). Exposure routes and health risks associated with pesticide application. Toxics, 10(6), 335.

Yet, **the labour-saving potential of automated precision technologies can overshadow concerns over labour displacement,** including farmworkers, pest scouts, and off-farm input applicators – raising crucial questions about who bears the costs of labour transitions and how they are addressed.[lxiii] The extent to which digitalization and automation displace and deskill workers varies across contexts and remains the subject of ongoing debate, but concerns of displacement remain particularly high for low-wage migrant workers often employed under precarious conditions and with limited access to opportunity to retrain or take on other work.[301,302,303] While precision agriculture creates a range of new jobs operating 'outside' the bounds of traditional agriculture (e.g., the tech advisors, data center workers, analysts, software engineers), more discussion is required on who can access these jobs, the nature of agricultural work, and risks to farmer and community-level decision-making, autonomy, and rural life.[lxiv,lxv]

Automated technologies also reshape labour conditions through surveillance, particularly on larger farms. Precision sprayers and GPS-equipped tractors enable farm owners or farmers to monitor farmworkers' hours and minimize their rest time, tightening control in the name of efficiency.[lxvi,304] Meanwhile, the data generated by farmers' and farmworkers' activities (e.g., monitoring and tending to crops and livestock) is what powers precision agriculture and their surveillance systems – effectively transforming farmers and farmworkers into data labourers without recognition or compensation.[305,306,307]

The emerging vision of the "farmerless farm" is only amplifying these risks. In 2019, Zibo Hefeng Seed Technology Co Ltd became the first unmanned farming operation in China, operating over some 33 hectares of land. More recently, Huawei and China Mobile Zibo set up the operation's first 5G site, providing the connectivity required to rapidly generate the large volumes of data it requires to function.[308] The possibility of reducing, if not eliminating, the role of labour on farms altogether deepens the marginalization of farmworkers and further undermines recognition of the value of farm work. It also assumes a global aspiration towards highly automated, data-driven service-based societies, detached from the land and embodied skills – disconnections that have been proven to drive both human illness and ecological breakdown.[309]

Impacts on autonomy, knowledge, and control

Precision spraying tools are touted as cost-saving for farmers, with results varying largely on farm size, crop and soil type, on-farm labor costs, and access to finance. For large-scale soybean and maize producers in Brazil, studies show a +50% cost reduction in pesticide expense per hectare.[310] A further study indicates a reduction of pesticide costs by 60-67% in small- and medium-scale apple orchards in the US when using variable-rate sprayers over conventional constant rate sprayers.[lxvii,311]

lxiii Pest scouts refer to the farmworkers or off-farm advisors who monitor and provide recommendations for crop health, ecosystem health, and/or disease development on a field. They are particularly used on farms relying on biocontrol methods (see below for more on ecological pest management).

lxiv Through interviews, Carolan also highlights concern among some farmers and farmworkers that the rise of robotics may undermine the agricultural sector's historical reliance on, and support for, immigrant labour in the US. Carolan, M. (2019). Automated agrifood futures: robotics, labor and the distributive politics of digital agriculture. The Journal of Peasant Studies, 47(1), 184–207.

lxv The impacts of "labour-saving technologies" on farming have been debated since early motorization. In the early twentieth century, the replacement of horses with tractors was subject to much debate. Proponents of horsepower expressed concerns about the high costs of machinery, the risks of technological lock-in, and threats to the livelihoods of horse carers, horse equipment manufacturers, and veterinarians. See Clapp, J. (2025). Titans of Industrial Agriculture: How a Few Giant Corporations Came to Dominate the Farm Sector and Why It Matters. MIT Press. pp. 52-53.

lxvi Historical research has also revealed early connections between agricultural labour management and the development of digital systems of control. Whittaker highlights how the logic underpinning modern computation was derived from earlier systems of industrialization and labour control on plantation systems meant to standardize, monitor, and control workers in the service of capitalism and colonial control. Whittaker, M. (2023). Origin Stories: Plantations, Computers, and Industrial Control. Logic(s), 19.

lxvii Variable rate precision spraying uses sensors, GPS, and data analysis to adjust the amount of pesticides required based on factors including soil type, crop health, or the presence of pests or disease.

Given the high upfront costs of these tools, however, farmers who adopt them are incentivized to maintain pesticide-based practices for years (or even decades) to recoup their investment. In doing so, they are effectively locked into conventional farming approaches rather than encouraged to adopt more holistic strategies that transition away from pesticide use.

Like many agricultural technologies before them, precision farming technologies have limited compatibility with older equipment, working best when integrated with complementary tools.[lviii,312] Rather than buy each new technology separately, farmers looking to fully integrate precision tools into their systems can reduce initial investment costs through bundled adoption. One study found that while variable-rate technology alone did not yield significant cost savings, it did when bundled with technologies like yield monitoring and soil mapping.[313] Digital platforms are essential here, as they centralize the monitoring and operation of these various technologies in one (online) location. Platforms like Bayer's FieldView are designed to reinforce a specific "brand ecosystem" to ensure profit:[lxix] FieldView integrates most seamlessly with partnered products, including John Deere equipment or machinery equipped with AGCO's Precision Planting monitors.

However, **bundling technologies may exacerbate socio-economic disparities between farmers, fueling farm consolidation.** In many cases, large, independent farms are better positioned to absorb the high upfront costs of precision tools and benefit from any efficiency gains.[314] This is likely reflected in the adoption rates of precision tools across farms and regions. In the USA, precision sprayers have been taken up by about 50% of larger farms, but only among 10% of the smallest farms.[315] While assessments remain anecdotal, adoption rates appear higher in North America,

China, Japan, and parts of Europe, whose larger-scale farms may benefit from better access to capital, advanced infrastructure, and agricultural policies that facilitate the uptake of these technologies – and where many agritech companies are based.[316]

Given record levels of farmer debt around the world, these costs are extremely prohibitive for most small and medium-sized farmers, unless coupled with government support or through pooling of resources. Limited broadband access and insufficient digital technical support further widen this gap.

Bundling strategies are nothing new, with major agribusiness companies pairing agrochemicals with the machinery to apply them as early as the 1940s and 1950s, or Monsanto promoting its patented seeds with its herbicides as "one-stop-shop" solutions for farmers since the 1990s.[317] Yet, **precision technologies are deepening technological lock-in by collecting greater amounts of farm-level data than ever before to influence input pricing, shape marketing strategies, and consolidate corporate control over the market.**[318]

This reflects a broader shift in agriculture towards "surveillance capitalism," the monetization of personal and operational data by corporations for commercial gain. Perpetuating a trend which began with the rise of Intellectual Property (IP) frameworks in the 1980s,[319] it represents an ongoing and concerted effort to commodify and capture data and place control in the hands of those who own digital data platforms.[320,321] As stated by Stucke and Grunes, the race among major agrochemical companies will be "to increase farmers' dependence on [their] digital platforms," who may even be required to purchase ongoing subscriptions or licenses to access their own data.[322]

lxviii Technological lock-ins have existed since early mechanization. For example, implements for horses could not be used with tractors, requiring farmers to buy into mechanization packages wholesale, regardless of whether they used these new technologies alongside previous tools. See Clapp, J. (2025). Titans of industrial agriculture: How a few giant corporations came to dominate the farm sector and why it matters. MIT Press.

lxviii A brand ecosystem is the one-stop-shop experiences provided by a company (or partnered companies) through interconnected products and systems. A main objective of developing brand ecosystems is to ensure customer loyalty and retention.

Precision spraying also raises a paradox for farmers' knowledge and autonomy. These tools can require steep learning curves to gain technological literacy (especially in contexts of aging farmers), going beyond traditional agronomic knowledge or the technical skills required to farm. Even farmers with high tech literacy have expressed frustration and major operational challenges in the adoption of these tools.[lxx] When precision tools break down, repairs often require a specialized technician to come to the farm,[323] which can result in several days of lost work depending on the technician's availability.[324] For example, research in the UK and Australia found that some farmers expressed frustration with the time required to fix technological glitches, interpret data, navigate data interfaces and regularly set up digital systems.[325] (See Section 1.1 for more on knowledge and precision technologies.)

In addition, **farmers are often prevented from overriding the decision-making process of programmed technologies.** Of the two companies that manufacture nearly half of all farm machinery equipment in the USA, both have leveraged copyright law to prohibit farmers from editing tractor software.[326]

In 2018, John Deere spent over USD1.6 million on federal lobbying, including to oppose "Right to Repair" legislation that would allow farmers to repair, retrofit, or adapt their machinery.[lxxi] As described in Section 1.1, while farmers can gain digital literacy from working with precision tools and complement this new knowledge with existing practices, they may also simultaneously lose agency as instincts, knowledge, and tacit expertise are deprioritized and replaced with the pre-programmed algorithms, data, and agronomic knowledge of "embedded knowledge technologies".[lxxii]

Lastly, as AI becomes indispensable for precision spraying, farmers are relying on fewer data platforms, including TensorFlow and PyTorch, bringing substantial amounts of agricultural land under the influence of a handful of data companies. Centralized data systems not only reinforce corporate control, but it also risks increasing security threats and the vulnerability of our food systems should these systems fail. (See Box 8 for more.)

lxx A number of farmers from North America, Europe, and Latin America shared these challenges during our interview process. In our previous work, one farmer in North Dakota mentioned the days "wasted" in trying to troubleshoot malfunctioning precision agriculture tools, ultimately abandoning the technology in subsequent years, despite a background in agriculture biosystem engineering. See IPES-Food, TABLE Debates & the Global Alliance on the Future of Food (2024). Episode 3: Do we need agrochemicals to feed the world?. Fuel to Fork Podcast.

lxxi John Deere went as far as claiming that farmers who purchased equipment from them do not own it, but own a "license to operate the vehicle". See Kelloway, C., and Miller, S. (2019). Food and Power: Addressing Monopolization in America's Food System. Open Markets Institute.; Clapp, J. (2025). Titans of Industrial Agriculture: How a Few Giant Corporations Came to Dominate the Farm Sector and Why It Matters. Chapter 12. MIT Press.

lxxii Embedded knowledge technologies refer to technologies that incorporate pre-programmed algorithms, data, and agronomic knowledge that require little to no additional skills or training to gain value from their use. "Embedded knowledge" technologies are contrasted to "information-intensive" technologies, which require users to have additional skills or knowledge to use them. Guided and automated sprayers are considered "embedded knowledge" technologies that make decisions based on algorithmic structures that are rarely explainable to the end-user or even the programmers themselves. See Naud, O. et al. (2020). Support to decision-making. In Agricultural Internet of Things and Decision Support for Precision Smart Farming (pp. 183-224). Academic Press; Castelvecchi, D. (2016). Can we open the black box of AI?. Nature News, 538(7623), 20.

BOX 8

WHEN SYSTEMS FAIL: THE (CYBER)SECURITY RISKS OF DIGITALIZED FOOD SYSTEMS

As stated by J. West, "There are two types of precision agriculture systems—those that have been hacked, and those that will be."[327] For example, the cyberattack on JBS, the world's biggest meat processor, led to temporary closure of the companies' operations in the USA, Canada, and Australia and an USD 11M ransom paid to the cyberattackers.[328] In the first quarter of 2024 alone, over 40 cyberattacks were already reported in the US agrifood sector.[329] And while large agrifood companies may be able to afford the ransoms demanded by cyberattackers, one study confirmed that over 60% of cyberattacks in the US since 2014 target small and medium-sized enterprises, including farmers, agricultural suppliers, and agribusiness firms, many of whom cannot financially recover from cyber crimes.[330]

Digitalized systems also escalate the potential for unanticipated and cascading failures, particularly in human–machine hybrid systems (including precision agriculture) where AI agents act faster than humans are able to respond.[331] Failures include the generation of false sensor data, ransomware attacks, or loss of control of data or machinery.[332] For example, in 2024, a ransomware attack on a Swiss dairy farm disabled the farm's automated milking equipment and data collection systems, resulting in the death of a pregnant cow.[333] In addition, outages, downtime, or signal interferences caused by floods, fires, and even space weather events (e.g., solar storms) or political instability can also drive additional vulnerabilities, likely to worsen as climate impacts intensify.

The unforeseen risks in digital systems threaten the lives of animals, farmers and farm workers, and the overall resilience of our food systems. As agriculture becomes increasingly reliant on digital infrastructure, these risks require urgent and ongoing assessment to safeguard against them.

Implications for power in food systems

Precision spraying technologies vary in their data processing capabilities and level of automation.[334] They span from prescriptive tools to fully automated sprayers that minimize human intervention. As these tools become more complex and interconnected (e.g., relying on mining supply chains, intensive data collection, algorithmic decision-making, and automation), the greater the conditions required to ensure their fairness, accessibility, and inclusivity.

As it stands, **precision spraying technologies are geared towards reinforcing industrial agriculture and the use of chemical inputs.** They prioritize short-term efficiency and productivity gains while failing to challenge the inequalities, environmental harms, and dependencies on chemical input systems they perpetuate. While precision spraying may reduce farmer, farmworker, and crop exposure to pesticides, it also enables the agrochemical industry to position itself as a critical player in addressing climate change and biodiversity loss, despite being a major contributor to these crises.

Nevertheless, under different conditions, some precision spraying tools *could* be reoriented towards more emancipatory and sustainable ends. This would require them to be integrated into paradigms that prioritize accessibility (e.g., affordability or collective ownership models), adaptability (e.g., compatibility with biopesticides and diverse cropping systems), and equitable governance (e.g., farmer and regulatory control over data and data assetization), while also ensuring farmers' and farmworkers' ability to override algorithmic decisions, access skilling and training programs, and stronger labour protection policies.

Fundamental questions remain on whether automated precision technologies are needed in the first place. While addressing drudgery and labour shortages are important, simpler (digital or non-digital) technologies often preserve greater farmer autonomy while reducing physical strain (see Section 1.2). For example, in India's government-supported Andhra Pradesh Community Managed Natural Farming (APCNF) programme, manually controlled drones are used to apply biopesticides and biostimulants more efficiently, reducing labour requirements and costs.

These possibilities, however, are still constrained by the disproportionate influence of major agrifood corporations over research and policy agendas through lobbying efforts, public-private partnerships, corporate philanthropy, and industry-sponsored research.[335,336,337] In the US, for example, public funding cuts have driven land-grant universities reliant on substantial donations from agricultural companies for research projects, compromising scientific integrity.[338] In South Africa, investigative journalists revealed that CropLife, the agrochemical industry's largest lobbying group, planned to establish itself as a licensing body to appoint its own scientists to conduct field trials for pesticide approval.[339]

In the EU, pesticide companies have spent millions lobbying to delay and dilute pesticide regulations,[340] with Bayer alone spending more than €30 million (USD 34 million) in EU lobbying efforts since 2020.[341]

Meanwhile, international research centers, including a number of Consultative Group on International Agricultural Research (CGIAR) centers increasingly rely on funding from private companies and corporate philanthropies to fund their projects.[342] This concentration of resources in research on pesticides and associated technologies drastically limits support for alternative crop protection strategies.

2.2

Credit: McKnight Foundation

ECOLOGICAL PEST MANAGEMENT

Ecological pest management (EPM) is one of the innovations for managing pests and diseases. It relies on a set of interrelated on-farm ecological processes, rather than off-farm synthetic inputs, to manage pest populations.[lxxiii] **Drawing from Indigenous foodways, farmer knowledge, practice, and research, ecological pest management includes social, technical, and ecological innovations adapted over centuries to agricultural systems around the world.**[343] As early as 1200 B.C., Chinese farmers developed biopesticides and fungicides to treat seeds and crops, and later used bamboo poles to encourage ants to climb citrus trees to combat pests.[344] EPM practices gained recognition within formal scientific disciplines in the late 19th century,[lxxiv] and were further established as a subset of ecological science in the mid 20th century.[345,346]

Often presented in contrast to chemical pesticide use, ecological pest management is valued for fostering ecological functions and more recently for reducing fossil fuel dependency. **As industrial agriculture has simplified and homogenized landscapes, many agroecosystems have lost their capacity to adapt and self-regulate.**[347,348] One recent study found that at least one tenth of global farmland lacks the minimal ecological functional integrity needed to support food production (i.e., the basic conditions for ecosystems to function, including pollination, soil protection, and pest regulation).[349]

lxxiii While the terms "biocontrol" and "integrated pest management" are well established in scientific and policy contexts, we prefer the use of "ecological pest management" to describe these and a wider set of practices. By focusing on control or domination, the term "biocontrol" can imply a narrow, utilitarian view of nature that overlooks the integrative and relational principles that underpin ecological pest management practices. It also fails to reflect the concept's historical grounding in worldviews and practices that emphasize interdependence among different forms of life. Similarly, integrated pest management (IPM) was originally intended to provide a holistic alternative to chemical-intensive forms of pest control, but it is now frequently practiced alongside heavy agrochemical use despite its original intent and due to industry pressures and the scaling up of IPM within industrial farming systems. It is also increasingly aligned with genetic technology, an approach we critically examine in Section 1.3.

lxxiv In particular, attention to biocontrol grew after the successful introduction of Australian beetles in California to combat pests devastating American citrus orchards in the 1880s. Kennett, C. E., McMurtry, J. A., & Beardsley, J. W. (1999). Biological control in subtropical and tropical crops. Handbook of biological control, 713-742.

By maintaining high levels of agrobiodiversity and supporting beneficial species, ecological pest management aims to support farming systems by preventing or limiting pest outbreaks in the first place.[350] These practices work with nature and strive to foster agrobiodiversity and increase resilience, emphasizing the long-term health and integrity of agroecosystems.[351] In many EPM systems, plants are understood as living beings able to foster complex interactions with other plants, microbes, animals, the soil, and abiotic factors.[352]

Particularly prevalent amongst small- and medium-scale farmers, EPM practices are highly adaptable to different scales and contexts, and cover practices most closely aligning with the principles of agroecology. Below, we focus on EPM approaches that harness ecological interactions, such as fostering natural predators or improving plant-insect relationships. (See Box 9 and Figure 4 for an overview of EPM practices.)

FIGURE 4

MANAGING PESTS WITHOUT CHEMICALS: ECOLOGICAL PEST MANAGEMENT IN ACTION

01. REDUCED TILLAGE	02. COMPOST	03. NITROGEN-FIXING LEGUMES	04. BIOSTIMULANTS	05. MULCHING	06. MANURE	07. CROP ROTATIONS
08. DIVERSITY OF CROPS	09. LOCALLY-ADAPTED VARIETIES	10. INTER-CROPPING	11. AGROFORESTRY	12. CROP-LIVESTOCK INTEGRATION	13. DIVERSIFICATION	

BOX 9

KEY PRACTICES AND DEFINITIONS OF ECOLOGICAL PEST MANAGEMENT

Ecological pest management practices can be differentiated by the specific techniques entailed and the role they play to ensure pest management and broader ecosystem health. Key practices include:

- **Biocontrol** involves the use of natural enemies, such as predators, parasitoids, or pathogens, to manage pest populations by either releasing them when needed (augmentative biocontrol), introducing non-native species for long-term control (classical biocontrol), or enhancing the habitats of existing beneficial organisms (conservation biocontrol).[353]
- In an EPM context, **biopesticides** are products derived from natural sources (e.g., bacteria, fungi, viruses, plants and minerals) to control pests. While some frame them as more ecological alternatives to synthetic pesticides, others argue that they are used as direct substitutes for chemical inputs and reproduce a logic based on killing pests rather than emphasizing prevention, protection, or addressing the underlying drivers of outbreaks.[354,355] Whether biopesticides can contribute to EPM remains contested, and depends on whether and how they can be integrated as part of a broader set of ecosystem-based practices.
- **Crop rotation** is the practice of alternating the types of crops grown in a particular field each season to disrupt pest and disease cycles (as non-host crops are included in the rotation) and improve soil health.
- **Cover cropping** involves planting crops that are not harvested to protect and enrich the soil, provide food and habitat for beneficial insects, and suppress weeds.
- **Hedgerows** and **flower strips** involve planting native shrubs and flowers along field borders to provide habitat for pollinators and natural pest enemies.
- **Intercropping** combines different crops grown together in time and space to foster a diverse range of beneficial organisms, make individual plants harder for pests to locate, and include plant species that repel or disrupt pests.[356]
- **Push-pull systems** use repellent crops to drive pests away from the main crop and trap crops to attract and divert pests from the target crops. Using this method, one crop in the fields repels pests (the "push"), while another plant, positioned around the field, attracts pests away (the "pull").

Ecological pest management also recognizes **the foundational role of living, microbially-rich soils, locally appropriate seeds**, and some physical tools (e.g., crop-protective nets) as essential elements for maintaining healthy crops. Enriching soil organic matter, including through manure and composting, can significantly increase soil microbial populations to help suppress diseases.[357] Synergies also arise when multiple practices are combined, further increasing agroecosystem resilience.[358] EPM also involves reliable pest monitoring (e.g., field observation or traps), early warning signaling and adjusting practices accordingly.

Impacts on ecosystem resilience and yields

Ecological pest management is promoted for its ability to ensure long-term pest and disease resilience while enhancing local ecosystem functions. It is worth noting that the diversity, complexity, and multifunctionality of ecological pest management methods can make them difficult to evaluate compared to industrial methods that are more easily quantifiable by mainstream metrics (e.g., methods that have measurable application rates and cause immediate crop yield responses).[359,360] EPM practices often require evaluating the breadth of ecosystem functions they contribute to (and draw from), isolating causality within complex natural interactions, or quantifying benefits that require longer monitoring times (e.g., impacts on local pollinator populations and beneficial species, long-term pest resilience).[361]

Many studies demonstrate the effectiveness of ecological pest management in keeping pest and disease pressures low over the long-term. For example, a global meta-analysis of 552 experiments found that plant diversification suppressed pests in 72% of cases and increased natural enemies in 74%.[362] On average, fields with high levels of plant diversity had 44% more natural enemies, 54% higher pest mortality, and 23% less crop damage than monocultures.[363]

A review of 200 studies comparing intercropping to monocropping found that intercropping reduced plant disease in 73% of the cases.[364]

At the regional level, research in Europe and North America shows 46% lower pest control efficiency on large industrial farming systems than on more diverse agricultural landscapes.[365] On small farms in East Africa, the push-pull method was shown to reduce pest damage to maize crops by 86.7% compared to untreated monoculture plots.[366] In Sub-Saharan Africa, a meta-study found that biocontrol methods reduced pest abundance by 63% and crop damage by over 50% compared to when biocontrol methods were not applied; natural enemy abundance also improved by 43% compared to agrochemical use.[367]

Understanding the nuances and complexities of natural interactions is crucial to EPM's success. For example, by nurturing overall agroecosystem health, EPM has generally been shown to target generalist predators (i.e., predators that eat a broad range of prey) better than it can handle specific pest outbreaks, though advances are being made in this regard.[368] (See Box 10 for a detailed case study.)

BOX 10

MANAGING THE SPREAD OF THE FALL ARMYWORM (SPODOPTERA FRUGIPERDA)

First detected in West and Central Africa in 2016 and later identified in South Asia in 2018, the fall armyworm has caused extensive crop damage that costly and harmful emergency pesticide-based responses have failed to resolve.[369,370] Annual maize yield losses due to the fall armyworm have been estimated at 33% in Kenya (2016-2017),[371] 45% in Ghana and 40% in Zambia (2017)[372], 33% in India (2018),[373] 36% in Ethiopia (2017-2019),[374] 22% in Burkina Faso (2020-2021).[375]

In response, EPM strategies including the deployment of nematodes[376] or the use of local biocontrol agents[377] have been developed as alternatives to chemical pesticides, supported by knowledge exchange opportunities between researchers, farmers, practitioners, and policymakers.[378]

To date, evidence points to the effectiveness of EPM strategies in managing the fall armyworm: in Uganda, infestation levels were 36-38% lower on farms using the push-pull method compared to a 95% infestation rate on single crop maize farms.[379] Similar benefits were experienced in maize farms in the Songwe and Manyara Regions of Tanzania, where farmers came together to share experiences and ideas on fall armyworm control.[380] In Malawi, farmer field schools and community-based knowledge sharing led to the development of effective and sustainable biopesticide innovations to combat fall armyworm outbreaks.[381] Farmers have also been exploring combining EPM practices, such as biocontrol and intercropping to prevent and manage infestations.[382] Effective monitoring and early warning systems, such as the FAO's Fall Armyworm Monitoring and Early Warning System,[383] have also been crucial in supporting these interventions.

Ecological pest management also distinguishes itself from agrochemical use by its ability to both enhance and protect ecosystems.[384] The ecosystem functions provided by natural biocontrol have been estimated to be worth an annual USD 50 to 160 billion in cropland alone.[385] By diversifying habitats, EPM can strengthen crop resilience to pests, diseases, and natural stresses (e.g., drought, nutrient deficiencies), while improving agroecosystem health over time (e.g., soil quality, biodiversity, water capture).[386,387] In Thailand, the use of hedgerows not only prevented soil loss and run-off by 62-86% and 31-69% respectively, but supported habitats for a diversity of natural enemies compared to conventional fields.[388,389] On rice farms, ducks and crabs are frequently introduced into the ecosystem to manage pests and weeds, while also aerating the soil.[390,391]

However, **as the impacts of EPM may sometimes take months or years to materialize, farmers may be discouraged to adopt these practices despite the long-term benefits they provide**, particularly for those farming on rented land or without secure tenure.[392,393,394]

As EPM strategies are most effective when implemented at landscape and regional scales, they also thrive best when supported by robust regional policy support, and coordination from the farm to the territorial level (see below).[395,396,397]

Lastly, t**he economic and environmental benefits of EPM appear to offset the potential reduction in crop yields often associated with plant diversification.** A meta-analysis of 552 experiments reported that yields largely depend on how diversification is implemented: when main crop plants were replaced by secondary species (either crop or non-crop plants), yields tended to decline. However, when secondary species were added without reducing main crop density, significantly increased yields overall.[398] Additional studies also highlight the challenges in comparing yields of organic or agroecological systems with conventional ones, as direct comparisons can overlook the unequal levels of support these two systems receive.

The "yield gap" between these systems may not only reflect a narrow focus on primary crop production, but also an investment gap in research and development, subsidization, and infrastructure.[lxxv,399]

Impact on autonomy, knowledge, and control

Ecological pest management has been touted for its cost-effectiveness, particularly compared to agrochemical use.[400,401,402] The initial investment costs in establishing more diversified agroecosystems, and the labour requirements to maintain them, may be high.[403] However, evidence suggests that EPM approaches ultimately lead to lower production costs, including significant cost-savings. For example, crop diversification reduces the need for synthetic inputs:[404] in France, increasing the number of botanical families[lxxiv] on fields reduced pesticide use by 23% for soybean cultivation, 21% for sugar beets, or 20% for sunflowers.[405] Increasing crop diversity *within* botanical families reduced pesticide use by 37% for potatoes, 20% for oilseed, and 14% for maize.[406]

From an R&D perspective, the contrast in product development between biocontrol and pesticide is equally stark: while developing a new pesticide has a 1 in 160,000 success rate and an average cost of USD 286 million per product, innovation in augmentative biocontrol methods[lxxvii] has a 1 in 10 success rate, at an estimated cost of USD 2.6 million per product.[407]

The benefits of EPM also extend beyond cost savings, with positive impacts on improving rural livelihoods, public health, and food security – particularly for smallholder and peasant farmers.[408] In Kenya and Uganda, the uptake of push-pull technology and integrated pest management since the mid-2000s have helped lift an estimated 30,000 people out of poverty each year across both countries; by 2021, every USD 1 invested in these practices generated an estimated extra USD 3 in returns.[409]

lxxv Effective EPM also depends on crops grown from robust, well-adapted seed varieties. As plant breeding and R&D have been historically underfunded in support of organic and agroecological systems, these systems often end up relying on varieties that are less resilient or poorly adapted to local conditions. As a result, agroecological and organic farmers may compensate by relying on heavy tillage or by expanding cultivated areas, both to the detriment of local soils and surrounding ecosystems.

lxxvi A botanical family refers to a group of plants that share similar physical characteristics or growth patterns. In agriculture, these can include cereals (poaceae) like oats, rice, corn, or millet or legumes (fabaceae) such as soy, beans, chickpeas, peanuts, etc.

lxxvii Augmentative biocontrol is a pest management strategy that increases the population of natural enemies of a pest by releasing mass-produced beneficial control agents into crops.

These practices have also been associated with ensuring food security for over 641,000 people.[410] However, applying EPM practices requires an intimate knowledge of local agroecosystems and combining the right types of plants, animals, and microbial communities both below and above the ground.[411] And unlike agrochemical use, EPM practices are also more difficult to standardize across different farming landscapes. As a result, **successful implementation of EPM relies on robust and accessible knowledge-generation and sharing mechanisms,** whether through participatory experimentation, peer-to-peer exchange, advisory services, and/or research and institutional support. Alongside scientific research, EPM strategies are deeply rooted in knowledge systems that build community autonomy, prioritize collaboration, and value human- and nature-centric approaches to innovation in which farmers are not simply users, but creators of knowledge.

Today, the promotion of EPM practices is championed by a wide range of actors, particularly Indigenous communities, organic and agroecological farmers, research institutions, civil society organizations, and non-profit groups. In particular, farmer-to-farmer exchanges and participatory research supported by non-profit organizations and research institutions have been instrumental in supporting, scaling out and continuously adapting EPM knowledge and practices on the ground.[412]

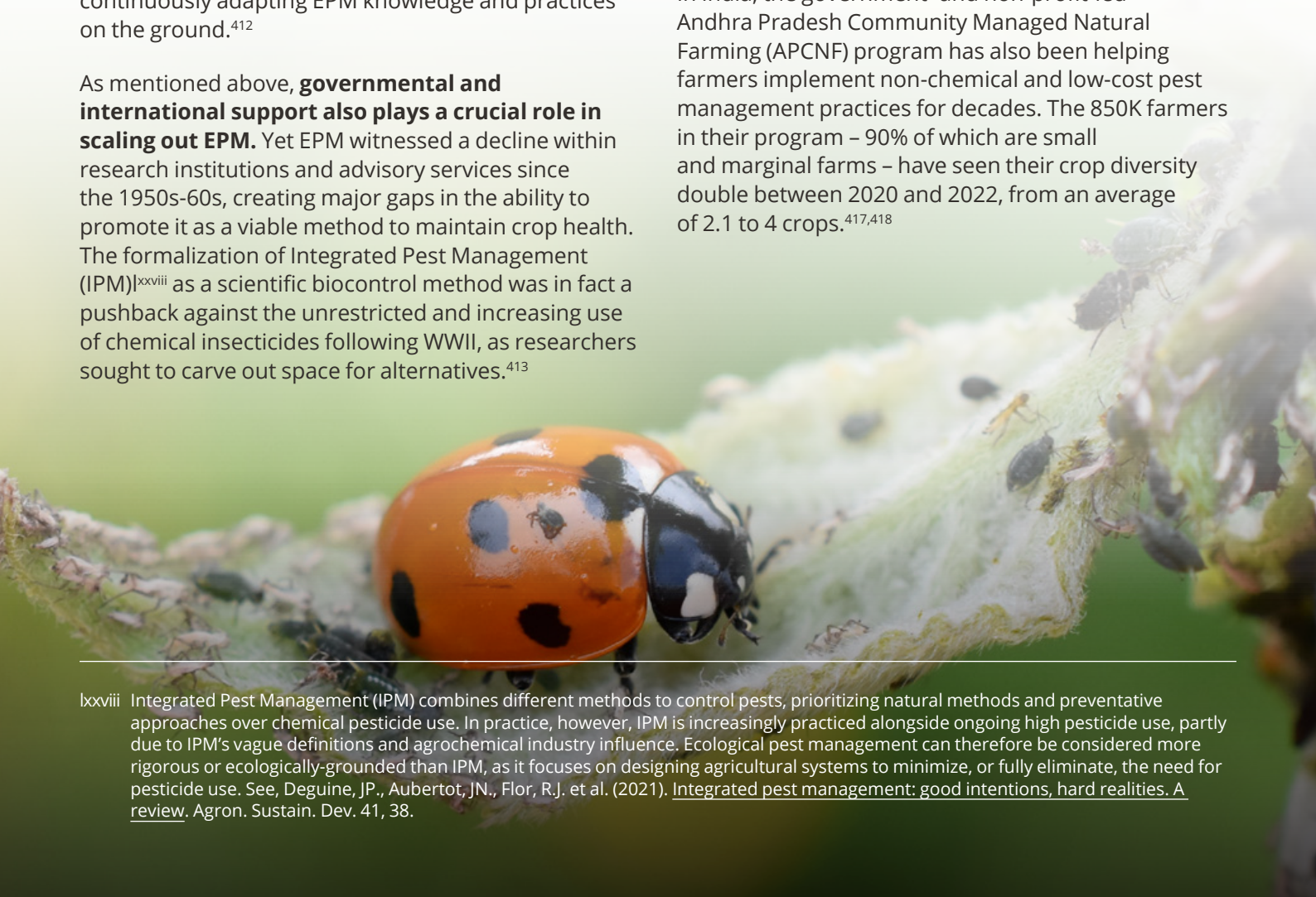
As mentioned above, **governmental and international support also plays a crucial role in scaling out EPM.** Yet EPM witnessed a decline within research institutions and advisory services since the 1950s-60s, creating major gaps in the ability to promote it as a viable method to maintain crop health. The formalization of Integrated Pest Management (IPM)[lxxviii] as a scientific biocontrol method was in fact a pushback against the unrestricted and increasing use of chemical insecticides following WWII, as researchers sought to carve out space for alternatives.[413]

For example, IPM programs implemented across one million hectares in the US in the 1970s and in South-East Asia in the 1990s achieved 70-80% pesticide reduction, but industry lobbying, increasing government support for pesticide use, and environmental deregulation were said to reverse these results in a matter of decades.[414]

An analysis of more than 3,000 publications on pest management in the Global South has also shown that scientific research lacks a holistic systems perspective – with more than 80% of the studies focusing on isolated tactics rather than integrated approaches to pest management.[415]

A number of institutions, including the FAO and the International Fund for Agricultural Development (IFAD), have long supported projects to increase awareness and uptake of EPM amongst smallholder farmers. Often based on fostering a culture of knowledge-sharing, many of these efforts have included training farmers to lead workshops within their own communities. For example, in 1999, 10 years after the introduction of the Indonesian government's national IPM program to limit pesticide use in rice production, over 50% of integrated pest management (IPM) Farmer Field Schools were led by farmers.[416]

In India, the government- and non-profit-led Andhra Pradesh Community Managed Natural Farming (APCNF) program has also been helping farmers implement non-chemical and low-cost pest management practices for decades. The 850K farmers in their program – 90% of which are small and marginal farms – have seen their crop diversity double between 2020 and 2022, from an average of 2.1 to 4 crops.[417,418]



lxxviii Integrated Pest Management (IPM) combines different methods to control pests, prioritizing natural methods and preventative approaches over chemical pesticide use. In practice, however, IPM is increasingly practiced alongside ongoing high pesticide use, partly due to IPM's vague definitions and agrochemical industry influence. Ecological pest management can therefore be considered more rigorous or ecologically-grounded than IPM, as it focuses on designing agricultural systems to minimize, or fully eliminate, the need for pesticide use. See, Deguine, JP., Aubertot, JN., Flor, R.J. et al. (2021). Integrated pest management: good intentions, hard realities. A review. Agron. Sustain. Dev. 41, 38.

However, as EPM gains recognition, **some narrow approaches to EPM practices risk reproducing dependencies associated with the agrochemical farming model, particularly in the case of biocontrol and in the use of biopesticides produced off the farm.** One study highlights that biocontrol efforts can be geared towards the development of "prescription-like" products rather than fostering procedural approaches that restore and enhance ecosystems.[419] As a result, farmers may still have to rely on external suppliers for predator species or bio-inputs, particularly when predators fail to establish permanent populations on site or when farmers lack the capacity or resources to produce on-farm inputs.[lxxix]

The rapid commercialization of biopesticides, biofertilizers, and beneficial insects also risks perpetuating reliance on costly external inputs, even as farmers and farming communities around the world continually develop their own bio-based inputs.[420] While investments remain proportionately small compared to agrochemical R&D,[lxxx] companies including Syngenta, Bayer, and BASF are investing millions of dollars in biopesticide R&D. Under the guise of sustainability, these efforts may simply be allowing major agribusinesses to maintain market dominance, shifting their profit from one proprietary product to another.

Implications for power in food systems

Despite its proven benefits, **a number of systemic factors continue to constrain the wider adoption and acknowledgment of EPM.** Though farmers around the world have practiced EPM methods for centuries, it remains poorly recognized, largely undocumented, and insufficiently supported by public policy.[421] Systemic bias and economic pressures continue to shape perceptions of which solutions are considered valid or not.

While agrochemical solutions can be tightly controlled and managed, EPM and related practices are positioned as riskier, less scalable, or less effective than agrochemical use – especially when generalizable, quantitative, and scientific evidence is privileged over qualitative, contextual, or experiential bodies of knowledge.[422,423,424]

Even when government programs and international initiatives include aspects of EPM, they remain marginal relative to the incentives and funding going into supporting and developing "improvements" to agrochemical solutions. These initiatives fail to consider beneficial organisms and plants as a form of effective long-term crop health insurance.[425]

Numerous studies have also pointed to the role of global subsidies, advisory services, and research funding mechanisms in encouraging the unsustainable use of agrochemical input over other alternatives.[426] For example, a 2020 study by CIDSE found that agricultural projects supporting "transformative" (in contrast to "incremental") agroecology only represented 10.6% of the Green Climate Fund's portfolio.[427]

Yet, EPM and related approaches have continuously demonstrated efficacy across diverse contexts and regions, particularly in small-scale, biodiverse agroecosystems. To this effect, a number of EPM studies have emphasized the need to embrace "variability in nature" and "ecological heterogeneity" within agricultural research. These realities challenge dominant approaches to evidence-gathering that focus on linear causal relationships and predictable, uniform results.[428] Acceptance of variability also highlights the need for observation, experimentation, and participatory knowledge-sharing mechanisms as crucial to successful crop management practices and innovations.

lxxix The production of on-farm biopesticides are also shaped by gender and class dynamics. For example, a study in India found that home-made biopesticides are highly time-consuming to prepare, and are primarily produced by women. However, smallholder family farmers and women farmers did not always have the time for biopesticide production, as they also often work as seasonal labourers, requiring wage work to sustain their livelihoods throughout the year. Wealthier households, by contrast, can hire labourers to carry out this task, making on-farm biopesticide production more accessible to higher-income farmers. Tozzi, A., & Still, E. (2025). The Ambiguous Ecologies of Agri-Alternatives: Exploring the Calculus of Social Reproduction in Rural India. Journal of Agrarian Change, e70048.

lxxx For example, agrochemical companies including BASF, Bayer, Corteva, and FMC only allocated 6.6% of a total USD 1.98B for R&D in biocontrol-based crop protection in 2019, compared to 93.4% of funds for chemical crop protection. This allocation was also slightly lower than in 2014, when the ratio was 7.3% (biocontrol) and 92.7% (chemical inputs). AgbioInvestor. (2024). Time and Cost of New agrochemical Product Discovery, Development and Registration.

3

INNOVATIONS TO ENSURE CLIMATE ADAPTATION AND RESILIENCE

In this section, we consider two different responses to ensure climate adaptation and resilience: gene-edited seeds and peasant seed systems. While gene-edited seeds are largely embedded in proprietary systems and tend to view resilience as improvements to individual plant traits, peasant seed systems are grounded in biocultural heritage, local governance, and ecosystem-based approaches. Below, we analyze how these approaches impact climate resilience and agrobiodiversity, control over plant genetics, food security, how knowledge is created and valued, and their implications for power and food sovereignty in food systems.

Climate change has become one of the most significant threats to agriculture, and an inescapable challenge in farmers' daily lives. In 2024, Northern India was hit with record-breaking temperatures, flash floods, and periods of severe drought that drove widespread crop failure and water scarcity for more than 330 million people.[429,430] In the US, extreme weather events are now responsible for 85% of crop loss, with repercussions on ecosystem health and future harvests that may not be felt for months, or even years.[431,432]

By 2050, the Intergovernmental Panel on Climate Change (IPCC) conservatively estimates that climate change could place up to 183 million additional people at risk of hunger.[433] Low-income regions in the Global South are the ones most affected, despite having contributed the least to climate change.[434] **The world's most vulnerable groups are also already disproportionately experiencing climate impacts** – including women, children, the elderly, ethnic minorities, migrants and displaced persons, and low-income communities.[435,436,437]

Smallholder farmers and Indigenous communities face particular vulnerability to climate change, often due to financial insecurity, and lack of institutional support and access to infrastructure.[438] These vulnerabilities are compounded by long histories of colonial extraction and market dynamics that have driven land dispossession, erosion of local food systems, debt and greater dependence on external inputs.[439]

Rural women are also feeling the uneven weight of climate change due to conditions anchored in patriarchal structures and colonial legacies: unequal access to land, credit, institutional support, and decision-making, as well as increased risk of gender-based violence during and after climate disasters.[440]

The agronomic impacts of more frequent and intense climate shocks are extremely worrying. Studies estimate that staple crops in climate-sensitive regions like South Asia and Sub-Saharan Africa could decrease by 10-30% by 2050 due to heat stresses and unpredictable rainfall.[441] Biodiversity loss could increase by 14% or more, alongside higher instances of drought, floods, wildfires, and temperature extremes.[lxxxi] In other words, every fraction of a degree in increased temperature will exacerbate existing threats to food security, public health, and the environment.

Ultimately, ensuring climate resilience means ensuring livelihood resilience.[442] Farmers and farming communities around the world are exploring the many ways they can mitigate and adapt to climate change, from improving weather and early warning monitoring to resource, crop, and livestock management practices. This section focuses on seeds and seed systems – the networks of actors, resources, and activities that supply farmers with seeds – as the foundation of our food systems, and as the basis of climate and livelihood resilience. Seeds represent life. Every seed variety is an innovation in itself, nurtured by centuries of farmers' knowledge, practice, and experimentation to meet cultural preferences, nutritional value, and local environmental conditions.

Domesticating plants, developing crops through traditional breeding and cultivation, and saving and exchanging seeds have been a part of our shared global heritage for millennia.[443,444] Seeds have traditionally been regulated and exchanged through peasant seed systems, often on a customary basis (i.e., through shared rules, norms, and traditions held at the community level).[445] Many seed systems today carry this legacy, embodying centuries of knowledge, practice, and care.

lxxxi Estimates suggest that even if we meet the 1.5 degrees threshold, biodiversity loss will increase by a minimum 14%. IPCC (2023). AR6 Synthesis Report: Climate Change 2023.

However, seeds have long been subject to appropriation, enclosure, and commodification. The colonial extraction and theft of seeds and plants began in the 1500s, enabling imperial nations to build wealthy agricultural industries.[446,447] In the mid-1800s, the large-scale commercialization of seeds in North America was driven by advances in farm machinery and fertilizers, leading farmers to cultivate much larger tracts of land.[448] As farm size grew, purchasing commercial seeds became more practical and time-efficient than traditional practices of seed selection and saving. The large-scale development of commercial hybrid seeds in the 1930s further contributed to the commercialization and privatization of seeds.[lxxxii]

The commercial seed sector is based on the sale of proprietary crop varieties, developed through conventional breeding (e.g., hybridization) or genetic engineering – all protected by complex intellectual property rights (IPR) (see more below).[449] **The seed sector is now highly concentrated and inextricably linked to the agrochemical sector,** through an over 40 year process of mergers and acquisitions, the development of stringent IPR, and massive investments in R&D.[450] Today, the top six commercial seed and traits companies control close to two-third of the global market – the top four of these companies also rank as the leading agrochemical companies.[lxxxiii,lxxxiv]

These many developments have driven the rapid loss of plant genetic diversity worldwide. Thousands of local plant varieties have progressively been replaced by a few genetically homogenous varieties. Today, **crop diversity is at an all-time low, with only four crops (maize, wheat, rice, and potatoes) making up 60% of the world's plant-based calories.**[451] According to the FAO, 75% of seed diversity has been lost over the 20th century, particularly since the Green Revolution of the 1960s.[lxxxv,452]

The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) has cautioned that seed diversity ensures many of the key ecological functions that underpin agriculture, and its erosion puts our food systems at greater risk of climate change, pests and diseases.[453]

Loss of seed diversity also has major implications for public health and nutrition. Crop diversity and thus dietary diversity have also been linked to improved nutrition outcomes at the household level, especially when coupled with other ecological farming practices (e.g., soil conservation) and social practices (e.g., farmer-to-farmer networks).[454] In addition, more than 60% of the global population – up to 80% in some communities – relies on wild and farmed plants as a primary source of health care.[455]

lxxxii A few commercial seed firms pre-date the industrial revolution. For example, the French company, Vilmorin, was created in 1743 as one of the first seed firms. It is now the fifth largest seed corporation in the world. Clapp, J. (2025). Titans of Industrial Agriculture: How a Few Giant Corporations Came to Dominate the Farm Sector and Why It Matters. MIT Press. Chapter 4. p.89.

lxxxiii In order of ranking, the top six seed companies include Bayer, Corteva Agriscience, Syngenta, BASF, Groupe Limagrain/Vilmorin & Cie, and KWS. ETC Group & GRAIN. (2025). Top 10 agribusiness giants: corporate concentration in food & farming in 2025.

lxxxiv In 2023, Bayer, Corteva, Syngenta, and BASF held 56% of the proprietary seed market and 61% of the global pesticide market. All four companies are now turning towards gene-edited seeds as new additions to their marketing toolkits (see more below). Syngenta and Bayer alone hold 42% of the commercial seed market. See ETC Group & GRAIN. (2025). Top 10 agribusiness giants: corporate concentration in food & farming in 2025.

lxxxv The cited figure of 75% seed diversity loss focuses on commercial varieties and does not include the diversity of traditional seeds maintained by individuals, communities, and seed banks. It is likely that many seeds continue to thrive within farming communities around the world, but are overlooked or unaccounted for in formal statistics. See La Via Campesina. (2021). Food Sovereignty born of Peasant Seeds.

3.1 GENE-EDITED SEEDS

Agricultural biotechnology is rapidly advancing, with gene editing (called New Genomic Techniques or NGTs) as its latest tool.[lxxxvi] An extension of genetic engineering, gene editing also involves the direct alteration of an organism's DNA in ways that cannot occur through conventional breeding. What distinguishes gene editing is the precision of certain tools, such as CRISPR, and the assumed speed at which targeted changes can be made.

Using this method, developers seek to introduce new traits into agricultural crops, including greater resistance to stresses such as extreme temperatures, pests, and diseases, or improved nutritional value, while claiming to reduce reliance on synthetic chemicals and increasing yields.[456,457,458] (See Box 11.)

lxxxvi NGTs are also known as New Breeding Techniques (NBTs) or New Genetic Engineering (New GE). New genomic techniques include zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) linked with a Cas protein (CRISPR/Cas).

BOX 11

GMOS, GENE-EDITING, NGTS: WHAT'S THE DIFFERENCE?

Gene editing is often presented as a new category of biotechnology, but scientifically it is best understood as part of genetic engineering. Both gene editing and earlier genetic modification (GM) techniques directly modify an organism's DNA using laboratory-based tools that can create changes not achievable through conventional breeding or natural selection. What gene editing offers is a suite of tools (e.g., CRISPR) that can target particular DNA sequences for modification in a wide range of organisms, including crops, livestock, and even microorganisms such as soil microbes (e.g., bacteria, fungi) used in fertilizers or (bio)pesticides.[459,460]

New Genomic Techniques (NGTs) that enable gene-editing are often described as "molecular scissors" due to the targeted nature of the technique. However, these tools do not simply "snip" DNA like scissors. They operate through complex cellular processes that require the insertion of foreign genetic material (e.g., guide RNAs, enzymes, and repair templates) into the cell to direct the change. Sometimes this inserted material is removed, sometimes traces remain and sometimes additional 'foreign' genetic material from non-sexually compatible organisms must be inserted to achieve the intended trait.[461] This contrasts with the method used to develop GM crops to date, where foreign genes (i.e., transgenesis) are inserted randomly into the genome, and not predetermined by the technique. Gene editing therefore sits within the broader continuum of genetic engineering, using different tools but following the same logic of altering DNA through human intervention as GM methods.

Since 2012, CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) – particularly in combination with the CRISPR-associated protein 9 to form CRISPR-Cas9 – has gained significant traction as a relatively simple and adaptable NGT technique.[462,463] It has been touted as a "game-changer" in the medical and agricultural fields in particular.[464,465,466] CRISPR can improve affordability and the speed of R&D, and claims potential to create new seeds up to 10 times faster than conventional breeding methods.[467,468,469] Building on CRISPR, many additional gene editing tools (e.g., advances in base editing, prime editing) are being developed, promising even greater accuracy and potentially lower risk of off-target effects.[470]

It is also often asserted that transgenic GMOs create 'unnatural' mutations, while NGTs can generate traits that could theoretically occur in nature or through traditional breeding.[471] However, this distinction is largely political rather than biological. Research shows that gene editing and earlier genetic engineering approaches produce overlapping types of mutations – including off-target changes, large deletions, insertions, and rearrangements – none of which follow natural mutational pathways.[472] In addition, gene editing, particularly CRISPR/Cas9, has been shown to make previously inaccessible and/or protected parts of the genome accessible for targeted modifications.[473] In practice, the mutations arising from both methods are laboratory-constructed and not equivalent to naturally occurring variation.

Some argue that attempts to distinguish gene-edited crops from traditional genetic modification deliberately seek to downplay their similarities and overlaps, especially when they share similar ecological and social risks (see below).[474] In fact, the European Court of Justice concluded that NGTs should fall within the definition of GMOs and be governed by the same regulatory framework, rejecting attempts to treat gene-edited organisms as fundamentally different techniques.[475]

Promoted by major seed companies, governments, and research institutions, gene-edited seeds are touted as vital tools to weather climate change. However, **while hundreds of gene-edited crops are currently under development,[476] only 11 have been approved for sale across five countries as of January 2026** – which does not necessarily reflect actual commercialization.[lxxxvii] Japan was the first country to commercially approve a CRISPR-edited crop in 2020: a tomato containing more gamma-aminobutyric acid (GABA) to lower blood pressure, developed by Sanatech Seed.[477]

The regulatory landscape for gene editing is complex and continuously evolving. Some frameworks focus on regulating the final plant product, others focus on the gene editing techniques themselves, with many making distinctions between gene editing for research purposes versus for commercial release. Gene-edited crops are still largely regulated as GMOs, in line with the Cartagena Protocol on Biosafety, with some countries including Norway[478] upholding strong values-based and precautionary regulations. To date, a minority of countries (less than 10% globally) are moving to relax or adapt their regulations to exempt gene-edited crops from biosafety laws for GMOs.[lxxxviii]

Agricultural gene editing startups have attracted over USD 2.7 billion in investment since the advent of CRISPR in 2012, with 82% of this growth driven by North American funding.[lxxxix] While universities and public research institutions hold many patents related to gene editing techniques, these are often for research rather than commercial use.

The commercialization of gene-edited seeds is therefore highly dependent on the influence of large seed corporations including Corteva, Bayer, and BASF, alongside a growing startup industry.[479]

Lastly, major international organizations are promoting gene editing in agriculture, including the CGIAR and the World Bank.[480]

Philanthropic organizations, such as the Gates Foundation, are also investing tens of millions of dollars in field trials, including gene-edited rice projects in India and corn trials in Mexico.[481]

Through the Gates Agricultural Innovations initiative, for example, the Foundation collaborates with Corteva to bring gene-editing technologies (amongst others) to smallholder farmers across the world.[482]

In the section below, we recognize that assessing the impacts of gene-edited crops for climate resilience remains challenging as very few have been commercialized and taken up by farmers.[483] As such, much of the discourse around gene editing is based on promotional claims and projected benefits, whose veracity needs to be substantiated. IP regulation further impedes transparent and independent assessment.[484] Our analysis therefore draws on limited available information, including research from field trials and early commercialization, critical analyses of gene editing's broader social, cultural, and political implications, and parallels drawn from studies on GMOs and traditional GM techniques.

Impact on climate resilience, pesticide use, and yields

Gene editing is being put forward as a tool for climate adaptation, with claims boasting greater resilience, lower input needs, and higher productivity. **Proponents argue that gene editing may be particularly useful in making crops resistant to non-biological stressors** (e.g., temperature extremes, droughts, floods).[485] For example, Bayer and Pairwise, a multimillion gene-editing start-up, are collaborating to develop a shorter stature corn more resistant to heavy winds and storms.[486] The Innovative Genomics Institute is developing drought-tolerant rice by reducing the number of stomata per plant – i.e., the microscopic pores that regulate water and gas flows.[487]

lxxxvii The five countries who have approved gene-edited crops include Canada, China, Japan, Philippines, and the United States. Five of the eleven approved gene-edited crops were developed using CRISPR. There are also three commercially available CRISPR-edited animals on the market – two in Japan and one in the US. See Global Gene Editing Regulation Tracker. Gene Editing and New Breeding Techniques: Regulations, Ratings and Index. Accessed October 21, 2025.

lxxxviii Countries that offer or are discussing case-by-case approval of gene-edited crops include Argentina, Bangladesh, Brazil, China, Colombia, Ecuador, Ghana, Honduras, India, Indonesia, Kenya, Malawi, Nigeria, Pakistan, Paraguay, Uruguay, and the United Kingdom. For example, Argentina and Brazil require gene-edited crops to be reviewed by a national commission to assess whether they fall under GMO regulations or not. See the Global Gene Editing Regulation Tracker. Accessed October 21, 2025.

lxxxix The rest of gene editing R&D funding comes from Asia (13%), primarily through China, and Europe (5%). Gabbio, S. (2024, August 21). Investment in agriculture gene editing grew 206% YoY in H1 2024, hinting at sector recovery and new momentum. AgFunderNews.

Some research is also conducted on how plants can capture and store more carbon, while increasing yields,[488] such as the Gates Foundation-funded RIPE project working to increase the efficiency of photosynthesis in cassava, cowpea, maize, soybeans, and rice.[489]

In reality, however, **the majority of gene-edited crops under development are not focused on climate-related concerns, but on a range of traits for commercial appeal** (e.g., cosmetic appearance), **storage** (e.g., shelf-life), **and improving the efficiency of industrial systems** (e.g., herbicide tolerance and compatibility with chemical inputs).[490] A 2020 review examining 231 market-oriented gene-edited crop studies found that only 3% related to abiotic adaptation (e.g., drought or temperature tolerance) and 16% to biotic stress tolerance (i.e., pest and disease resistance); more than 30% of studies were to increase the agronomic value of crops (e.g., yields, efficiency), 25% addressed increasing food and feed quality (e.g., nutritional value), and 7% for herbicide tolerance.[491,492] A similar review of 49 gene-editing projects found that only 2 of the 49 crops being developed were for abiotic adaptation tolerance, 4 to biotic tolerance.[493] And while the diversity of gene-edited crops is much broader than first generation GMOs, it remains limited: of the 49 projects assessed, 63% were being conducted on only 5 crops: maize, soybean, rice, wheat and potato.[xc,xci]

Proponents of gene-editing seeds often claim that NGTs are a crucial part of the "Second Green Revolution".[494,495] Yet breeding priorities indicate that **NGTs risk reinforcing an industrial agriculture model based on uniformity, chemical dependency, and large-scale mechanized systems.**[496] For example, in early 2023, BetterSeeds announced the start of field trials of the first gene-edited cowpea designed for mechanized harvest.[497]

In addition, **questions remain on whether gene editing can truly reduce chemical input use, given mixed evidence to date.**[498]

A 2014 meta-analysis assessing the impacts of GM crops on pesticide use since 1995 found that while insecticide-resistant crops reduced insecticide use by an average of 42%, herbicide-resistant crops led to an overall increase in herbicide application.[499] This rise is largely attributed to the low cost and efficiency of broad-spectrum herbicides (e.g., glyphosate), a concerning trend as herbicides are the most extensively used and some of the most hazardous pesticides around the world.[500,501,502,503]

The claim that gene-edited seeds will lead to higher yields may also be overly simplistic and speculative. While some studies have reported yield benefits in laboratory settings and early field trials,[504] there remains a lack of real-world evidence demonstrating yield increases on the farm.[505] The FAO also notes that the ability of gene-editing technologies to improve yield is unlikely to be universal, and will likely remain limited to specific crops and environmental conditions.[506]

In addition, claims that gene editing is "precise" downplays the fact that **little is known on how gene editing may alter biochemical pathways or spread traits to other plants and impact ecosystems.** To date, no robust studies have examined the potential environmental impacts of gene edited crops.[507,508,509] Even the most precise DNA edits could produce unintended biological and ecological consequences due to our incomplete understanding of gene-editing technologies and how they impact complex biological systems functions.[510,511]

Lastly, the belief that resilience can be achieved by tinkering with a plant's genetic traits obscures the complexity of biology and broader ecosystem interactions.[512] **Studies indicate that conventional breeding continues to outstrip genetic editing and modification in developing more climate resilient seeds,** largely due to the genetic complexity that allows for these traits to express.[513] Researchers have also stressed that it is both difficult and impractical to expect gene editing to replicate the "thousands of mutations that have fine-tuned" crop production over centuries.[514]

xc The main countries developing these crops are the US (30 out of the 49), China (8), Brazil (6) and Argentina (5). European Non-GMO Industry Organisation, Non GMO Project & Semnar. (2025). New GMOs Market Report.

xci Gene-edited crops are also being developed to serve other industries, including the energy sector. For example, a number of gene-edited crops are specifically being designed to increase the efficiency of biofuel production, often through partnerships with major fossil fuel companies: Bayer, Bunge, and Chevron are collaborating to modify the oil profile of pennycress. See, Bayer. (n.d.) CoverCress. Accessed September 12, 2025; Bayer. (2022, August 1). Bayer expands existing investment to acquire majority share in sustainable lower carbon oilseed producer CoverCress Inc.; Garg, D., Samota, M. K., Kontis, N., Patel, N., Bala, S., & Rosado, A. S. (2023). Revolutionizing biofuel generation: unleashing the power of CRISPR-Cas mediated gene editing of extremophiles. Microbiological research, 274, 127443.

Impacts on autonomy, knowledge, and control

Research and policy discourses tend to separate "risk" from "ethics," treating them as unrelated spheres. As a result, wider social concerns (e.g., around consumer choice, seed sovereignty, appropriation of knowledge) are often left out of assessments of gene editing's safety and risks.[515] However, these concerns are highly relevant as gene editing technologies are developed within a highly concentrated sector dominated by a handful of seed and agrochemical corporations, who also control the majority of gene-editing patents.

CRISPR/Cas9 provides a clear example of how contentious and complex patent arrangements can be. Representing a multibillion-dollar market opportunity, it has been at the center of patent battles since its discovery.[xcii] The main patents for CRISPR/Cas9 are now held by UC Berkeley and the Broad Institute (a biomedical and genomic research center owned by MIT and Harvard). While the technology is available for research use, licensing is still required for any commercial application, managed by surrogate companies set up by CRISPR's inventors, and by Corteva in the case of agricultural uses.[516,517] (See Box 12.)

BOX 12

CORTEVA'S CAPTURE OF CRISPR: CONSOLIDATING CONTROL OVER GENE-EDITING TECHNOLOGY

To date, the foundational patents for CRISPR gene-editing technologies are largely held by public research institutions and universities, which grant exclusive licenses to private companies for their use for commercial crop development. Within this licensing system, Corteva (formerly DowDupont) holds the largest number of exclusive rights to develop commercial crops and new seed varieties using CRISPR technologies, alongside Bayer, Syngenta, and BASF[518] – which have collectively been labelled by some as a seed "patent cartel".[519,520]

In 2011, DuPont acquired Danisco, a pioneer in using CRISPR to enhance bacterial immunity in yogurt cultures and holder of crucial CRISPR-related patents, for USD 5.8 billion.[521,522] In 2015, DuPont then secured exclusive agricultural licensing rights for Cas9 gene-editing technology from Vilnius University and cross-licensed its patents with Caribou Biosciences, a surrogate company founded by CRISPR pioneer, Jennifer Doudna.[523] Corteva's dominance was further solidified in 2017 through two significant agreements: an exclusive licensing deal with ERS Genomics, a company founded by the CRISPR's other inventor Emmanuelle Charpentier, and a joint non-exclusive licensing agreement with the Broad Institute.[524] As a result, Corteva has become the leading agricultural gene-editing company worldwide, with major influence over the pathways through which CRISPR technologies can be legally commercialized in seed markets.[525] In practice, any entity willing to commercialize CRISPR-edited crops needs licensing from Corteva.

xcii The dispute involved Dr. Feng Zhang's group from the Harvard-MIT Broad Institute and Nobel laureates Dr. Jennifer Doudna (University of California, Berkeley) and Dr. Emmanuelle Charpentier (University of Vienna). Both groups filed

Intellectual Property in the hands of very few players can create major barriers to entry, limiting competition and driving up costs.[526] The financial barriers are significant: applying for and maintaining patents and associated legal fees can cost thousands – if not hundreds of thousands – of dollars, potentially excluding smaller breeders.[527,528,529] High licensing fees for NGTs create further obstacles, often forcing small seed companies to absorb early-stage costs and risks, only to be bought out by larger companies once their ideas prove viable and/or their capital depleted.[530]

Patents on gene-edited traits are also likely to increase costs for farmers, exacerbating already high seed prices. Between 1990 and 2020, for example, conventional seed prices in the US rose by more than 100% and GM seed prices by 463%, while crop prices only rose by 56% over the same period.[531] These higher costs have generally been attributed to corporate concentration, intellectual property rights, and rising R&D costs.[532] As patents and other IPRs (e.g., plant breeders' rights, plant variety protection, trade secrets) also restrict the ability to breed, save, and sell improved varieties, farmers become more dependent on corporate-owned seeds, forcing them to buy new seed each season – risks likely to be accelerated and incentivized with NGT seeds.[533]

At the same time, **corporate monopolies undermine the very rationale of IP rights,** originally meant to encourage experimentation, innovation, and investment in R&D. While agriculture-related gene-editing startups have raised over $2.7 billion since 2012,[534] a handful of corporations effectively act as gatekeepers of agricultural innovation and knowledge, skewing research incentives through acquisition, licensing deals, or partnerships with these smaller actors – including Corteva's USD 25 million investment in Pairwise.[xciii] Corteva alone invests USD 4 million per day on R&D.[xciv]

Indeed, in 2023, a USDA report highlights how seed industry consolidation has limited innovation, reduced genetic diversity of major crops (e.g., corn, soy and cotton), and increased risks to climate stresses and new pathogens. For example, the report emphasizes that genetic diversity of maize is largely being upheld by off-patent lines; over the last 20 years, the largest seed companies have done little to introduce new genetic diversity and have instead primarily worked to recombine existing traits within a narrow genetic base.[535]

In addition, some patents not only cover gene-editing tools themselves, but also specific genetic sequences, effectively making parts of crop genomes corporate property. **A single patent can encompass thousands of genes, granting patent holders extensive control over genetic resources.**[536] Beyond cost constraints, this has major implications on the ethics of and right to patent life and on many cultural relationships with seeds (as living entities and part of a cultural commons). Patenting plant genetic material also furthers a lack of recognition of thousands of years of breeding work done by farmers and communities around the world. In some cases, major companies can even use gene-editing to patent traits found in conventionally bred varieties.[xcv]

xciii Pairwise, a leading startup in agricultural gene editing, commercialized the first CRISPR feed in North America (a milder and less bitter mustard). Dr. Feng Zhang, a leading researcher in developing and applying CRISPR technologies, is one of the startup's scientific founders. In 2024, Corteva invested in and formed a joint venture with Pairwise to accelerate the development of Fulcrum, Pairwise's toolbox of proprietary CRISPR technologies aimed at "increasing crop yield for food, fuel and fiber production, despite increasing climate change." This venture allows Corteva to access key gene-editing patents, consolidating its dominant position in this space. Pairwise is also currently partnering with Bayer to develop "smart corn". See Pairwise. (2023, 29 August). Pairwise, Bayer Build On Successful Gene Editing Partnership With New Five-Year, Multi-Million Dollar Collaboration to Further Advance Short-Stature Corn; Pairwise. (2024, 17 September) Corteva, Pairwise Join Forces to Accelerate Gene Editing, Advance Climate Resilience in Agriculture.

xciv While breakdown of these R&D costs was not available, the company's 6 areas of focus include: seed and trait licensing, biologicals, new crop protection technologies, gene editing, biofuels, and advances in hybrid wheat. See Corteva. (2024, November 19). Corteva Highlights Breakthrough Innovation, Unveils New Financial Framework.

xcv For example, Nordic Maize breeding (NMb) is a small Dutch seed company that spent 20 years developing a cold-resistant maize variety, working with organic farmers and breeders through conventional breeding methods. However, KWS, the world's sixth largest seed breeding company, used NGTs to develop the same trait and secure a patent for it, threatening the security of Nordic Maize breeding's business and breeding efforts. See Brzeziński, B. & Andrés, P. (2024, February 6). Patent war looms over Europe's future supercrops. Politico.

The commodification of seeds is part of a long history of enclosing the biological commons through patenting and the privatization of seed rights.[537] From the US Plant Patent Act of 1930, the establishment of the International Union for the Protection of New Varieties of Plants (UPOV) in 1961, and the WTO's Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) in 1995, **legal frameworks around the world have progressively extended IP protections over plant varieties to the benefit of major seed companies and to the detriment of the seed systems that have sustained agriculture for millennia.**[538,539] As Kloppenburg argues, the development of commercial plant breeding breached social and biological barriers, allowing corporate interests to capitalize on nature as well as Indigenous and traditional farming knowledge.[540]

In this regulatory context, benefit-sharing from the use of genetic resources is rarely equitable, when it is even considered. The term 'biopiracy'[541] refers to the commercial exploitation and appropriation of biological resources (e.g., genetic materials, breeds, land), traditional knowledge, and people without recognition or compensation to those who nurtured them. It is rooted in colonial legacies perpetuated by governments, private actors, and research institutions.[542] In particular, women and Indigenous communities, as custodians of traditional seed systems, face disproportionate impacts from the privatization of seeds and the appropriation of genetic resources (see Section 3.2).

Tensions over whose knowledge counts as "sound science" are particularly prevalent in gene-editing debates today: by positioning gene-editing as the benchmark of science-based innovation and painting resistance as "anti-science" or "anti-innovation", proponents of gene-editing reinforce knowledge hierarchies between biotechnology and its alternatives, including peasant and Indigenous seed systems.

In practice, this has translated into greater investment in and attention to biotechnological science since the 1980s, and the active underdevelopment of agroecological research.[543]

Universities and public research institutions play a role in maintaining these hierarchies. Technology transfer offices are designed to channel publicly funded research to private companies, effectively aligning academic incentives with corporate agendas.[544] Public institutions' growing reliance on private funding further skews public research priorities, and creates path dependencies that risk constraining the future of agricultural innovation – and the infrastructure, training programs, and knowledge systems that accompany them.[545]

The integration of AI into biotechnology development is also fundamentally altering how varieties can be developed. Digital technologies are enabling plant genetic material to be translated into digital information (referred to as "biodigitalization", see Box 13). In particular, Digital Sequence Information (DSI) – the digital representation of genetic sequences (e.g., DNA, RNA, or proteins) – is now being aggregated into (Big) data sets and made available on public digital databases.[546] AI can then process this data to suggest new plant genomes, placing Big Data technologies in the driver's seat of breeding decisions. While a large portion of DSI is based on traditional varieties developed by farming and Indigenous communities, this process is allowing companies to claim patents on plant varieties and materials derived from DSI without physically accessing plants or sharing benefits with local communities.

BOX 13

BIODIGITALIZATION: WHEN BIOLOGY BECOMES DIGITAL DATA, AND DIGITAL DATA BECOMES BIOLOGY

Biodigitalization refers to the convergence of biological and digital technologies, through a two-way process of digitalizing biology and biologizing information. The combination of nanotechnologies, biotechnologies, information technologies, and AI has made it possible to translate plant genetic resources into digital information, and back again, "transforming digital data into breeding decisions".[547] For instance, genomic Big Data can be integrated with farm data to develop microorganisms or seeds tailored to combat diseases or environmental stresses detected live on the fields. Bayer's USD 100 million joint venture with synthetic biology leader Ginkgo Bioworks aims to genetically engineer microbes to improve nitrogen fixation abilities of soils degraded by industrial agriculture.[548]

Many are also claiming that biodigitalization, big data analytics, and AI could dramatically increase the speed at which trait discoveries can be made. For example, start-ups like Sweden-based OlsAro are developing climate-resilient crops using "AI-enabled trait discovery."[549] Tech giants are also getting more involved: Evo 2 is the largest biology foundation model in existence, focused on biomedical research.[xcvi] Developed by tech giant Nvidia and the Arc Institute, Evo 2 is learning from over 9 trillion DNA and RNA nucleotides and 128,000 genomes.[550] Proponents argue that models like these could not only speed up research, but also be used to predict how seeds perform under specific environmental conditions, assess seed viability, catalogue genetic diversity, or identify resilience traits in heirloom and wild relatives.[551]

Implications for power in food systems

As stated by Michael Fakhri, UN Special Rapporteur on the Right to Food, "to control seeds is to control life."[552] Seed sovereignty means having control over the crops one grows, the type of agricultural system one engages in, and how one chooses to interact with its ecological environment. Yet, gene-edited seeds are a product of innovation systems that understand science as a way to control and separate humans from nature.[553]

Gene-editing technologies come with significant risk. They are embedded in corporate seed systems, and the intellectual property regimes that uphold them come into direct conflict with seed sovereignty and many human rights. **Resistance to gene-editing from farmers organizations, civil society groups, and NGOs persists, building on decades of mobilization against industrial plant breeding,** from the hybridization of seeds to the early days of genetic modification.

These movements frame NGTs as part of an ongoing practice of capitalist and colonial extraction and exploitation that prevents communities from defining their relationship with nature and food systems outside of corporate control.[554,555] They highlight that NGTs largely rest on hypothetical achievements and promised future benefits that could be achieved by other proven means with far less social and environmental risk.[556] For example, strong breeding programs, farmer-researcher partnerships, peasant seed systems, or ecological pest management offer ways to reduce external input use and improve resilience without reinforcing corporate control.[557]

xcvi Biological foundation models are large AI systems trained on vast amounts of unprocessed biological data (e.g., gene sequences, chemical structures) to learn and identify biological patterns and relationships.

In reaction to these concerns, **a number of international treaties and agreements have attempted to protect farmers and Indigenous communities' rights and address these power imbalances.** The UN Convention on Biological Diversity's Nagoya Protocol in 2010,[xcvii] the UN FAO's International Treaty for Plant Genetic Resources for Food and Agriculture (ITPGRFA) in 2004, the UN Declaration on the Rights of Indigenous Peoples (UNDRIP) adopted in 2007, and the 2018 UN Declaration on the Right of Peasant and Other People Working in Rural Areas (UNDROP) all include provisions to ensure fair and equitable benefit-sharing from the use of genetic resources. Both UNDRIP and UNDROP also affirm the rights of local and Indigenous communities to maintain, control, protect, and develop their cultural heritage, including seeds and traditional knowledge.[558]

More recently, Parties to the Convention on Biological Diversity COP15 in 2022 agreed that the benefits from the use of DSI of plant genetic resources should be shared fairly and equitably through a multilateral system.[xcviii] Adopted in 2024, the World Intellectual Property Organization's (WIPO) Treaty on Intellectual Property, Genetic Resources and Associated Traditional Knowledge (GRATIK) is also aiming to address the lack of transparency and benefit-sharing in patenting systems. GRATIK aims to establish mandatory patent disclosure requirements, including the use of any Indigenous or traditional knowledge. Thus far, however, contracting parties to the treaty are almost exclusively governments from the Global South.[559]

Indeed, many of these treaties and policies struggle to be enforced due to the influence of biotech-leading countries in skewing policies to their advantage. [xcix,560] For example, countries that have chosen not to ratify the Cartagena Protocol on Biosafety – such as the US, Canada and Argentina – dominate global R&D, seed ownership, and the commercialization of agricultural biotechnology.

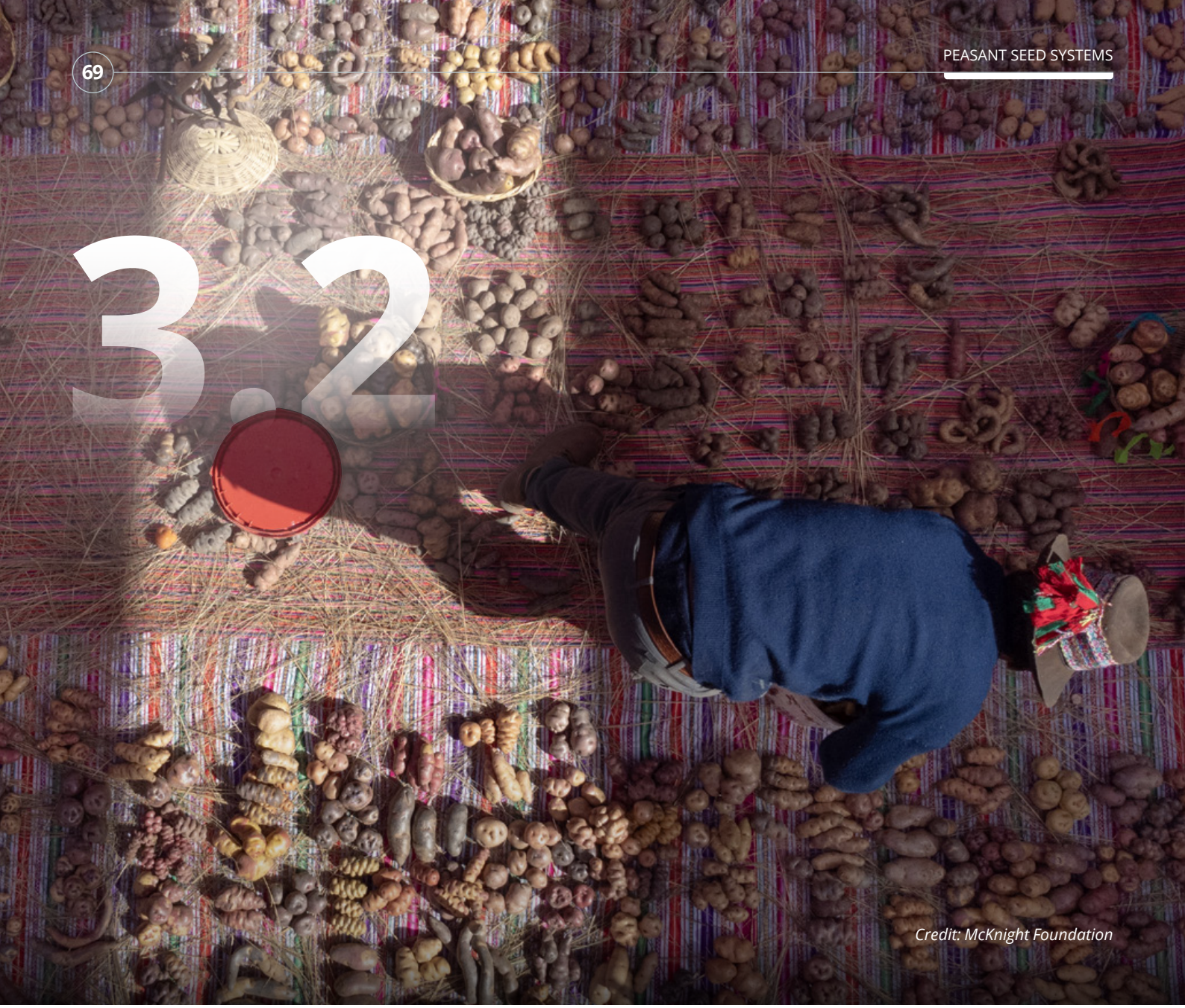
Global North countries are also failing to meet their obligations under the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) (e.g., around benefit-sharing, capacity-building, support for plant breeding research).[561] Meanwhile, they're exerting pressure on governments in the Global South to adopt seed and IP laws to privatize genetic resources in the name of food security, but effectively entrench them into a system of patent payments and licensing fees.[562]

There is also evidence that agrifood and tech industries play a major role in shaping national and international regulatory frameworks around biotechnology. In the EU, agribusinesses are pushing for deregulation around gene-edited crops.[563] In the US, investigations revealed that a US government-funded "private social network" was funded to monitor and criticize pesticide and anti-GMO critics in Africa, Europe, and other regions, while discrediting sustainable farming approaches to protect corporate interests and create dissent.[564]

xcvii The Nagoya Protocol (fully entitled the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization to the Convention on Biological Diversity) was an addition to the 1992 Convention on Biological Diversity (CBD) signed in 2010. It is currently ratified by 142 parties of the CBD (141 member states and the European Union).

xcviii The modalities to operationalize this decision were agreed upon at the following COP in 2024. See CBD. (2022). CBD COP Decision 15/9: Digital sequence information on genetic resources.

xcix For example, the Nagoya Protocol states that genetic resources, including key food crops, can only be exchanged if prior consent and benefit-sharing agreements are in place. However, major seed-exporting countries including Australia, Canada, and the EU have sought to relax these arrangements.



Credit: McKnight Foundation

PEASANT SEED SYSTEMS

Farming communities around the world acquire seeds in different ways, including through commercial seed markets, government programs, NGOs, and/or local seed saving and exchanging practices. In some regions, peasant seed systems (also called "farmer seed systems" or "farmer seed networks") supply farmers with the vast majority of their seeds, and remain vital to global food security (see Box 14 for definitions).

In Kenya, for example, around 70% of seeds are supplied through peasant seed systems.[565]
A study across Malawi, Kenya, the Democratic Republic of Congo, Haiti, South Sudan, and Zimbabwe similarly found that smallholder farmers accessed 90% of their seeds through peasant seed systems.[566]

BOX 14

DEFINING PEASANT SEEDS

In this section, we use the term **"peasant seed systems"** (rather than farmer seed systems or networks) to acknowledge farmers' and rural communities' right to control their own seeds. These seed systems refer to the set of practices and knowledges involved in the production, saving, and exchange of plant varieties bred and maintained by peasants.[567] These systems are largely managed by small-scale, Indigenous, and women farmers in the Global South.[568,569,570]

The term **"peasant seed"** is a relatively new concept born out of resistance. Coined by La Via Campesina (LVC) and allied movements in the early 2000s, it opposes the rapid privatization of seed systems. In their global campaign "'Peasant Seeds: a Heritage of Peoples in the Service of Humanity", LVC and allies emphasize that seeds are not commodities, but the heritage of Indigenous Peoples and peasants, who have bred, adapted, and conserved them for generations, and shared them with humanity.[571] This framing challenges corporate narratives that treat seeds as a "common heritage" anyone can benefit from – or exploit.[572]

These struggles also paved the way for the concept of **"seed sovereignty"**, i.e., the right of peoples to save, use, exchange, and sell their own seeds.[573] Seed sovereignty challenges corporate enclosure, state control, and the overreach of some private philanthropies in the governance of seeds. It also calls into question the broader political structures that undermine community autonomy and the right to self-determination.[574]

Peasant and Indigenous seeds have been selected, developed, and preserved by farmers and communities worldwide.[575] These seeds can be cultivated, semi-wild, and wild. Today, close to 3,000 wild species of plants are being harvested for human consumption, alongside an estimated 6,000 plant species domesticated over centuries.[576]

Peasant seeds are embedded in social and cultural life – exchanged or gifted within families and rural communities, bartered, or sold in formal and informal markets.[577] They rely on knowledge, reciprocity, and trust within and between communities, passed on and continuously adapted.[578,579,580] Women and Indigenous Peoples are often the primary stewards and custodians of seed knowledge in their community: by selecting, breeding, and tending to seed diversity, they have played a central role in ensuring local biodiversity and community resilience across generations.[581,582,583]

These seeds are also tied to traditional and Indigenous knowledges, spiritualities, cosmologies, and belief systems that fundamentally differ from those underpinning the commercialization and commodification of seeds.[584,585,586] In many cultures, seeds are understood as part of the sacred fabric of life, in which nature and culture are inseparable.[587] In this context, seeds are only able to thrive when treated with care and respect.[588] They represent livelihood, well-being, cultural heritage, respect for community ancestors, and ecological relationships.[c]

c Community events are also spaces that illustrate how seed exchange is embedded in cultural life and broader cosmologies. For example, at the Shwe Kyun Pin Nat Festival in Upper Myanmar, the Rice Harvest Festival in the The Naxi Mountain Villages of China, or the Watunakuy festival in the Andes, seeds are exchanged as blessings for good harvests, celebrated through song, dance, and storytelling, and shared to diversify seed strains across communities. See Nagashima, M. et al. (2022). Seed System Dynamics and Crop Diversity of Chinbaung in Myanmar. In: Nishikawa, Y., Pimbert, M. (eds) Seeds for Diversity and Inclusion. Palgrave Macmillan, Cham; Pimbert, M. (2022). Reclaiming Diverse Seed Commons Through Food Sovereignty, Agroecology and Economies of Care. In: Nishikawa, Y., Pimbert, M. (eds) Seeds for Diversity and Inclusion. Palgrave Macmillan, Cham; Chinese Farmers' Seed Network (2022). Living Seeds and Resilient Bio-cultures.

Impacts on climate resilience, yields, and food security

Peasant seed systems are put forward as a key contributor to climate resilience and food security by continuously breeding and reviving seed varieties, ensuring agrobiodiversity.[589] Peasant and Indigenous seed systems rely on traditional varieties, new cultivars, landraces,[ci] and crop wild relatives overlooked by commercial agriculture. While commercial seeds are bred for uniformity and predictability, **the seeds developed through peasant seeds are inherently heterogeneous and highly diverse** (across and within varieties), co-evolving with local soils, climate, and cultivation practices over generations.[590,591] For example, one study conducted in Mexico, estimated that peasant farmers were growing over 114 maize varieties per hectare in 2010, with each plant (estimated at 1.38 billion single plants) holding different genetic material.[592]

While assessing agrobiodiversity's importance for climate resilience remains challenging,[593] studies show that genetic diversity safeguards against crop failure and strengthens the ecological processes that support them.[594,595] For example, a meta-analysis of 91 studies covering over 3,600 observations found that sowing mixtures of crop varieties of the same species in the same plot increased yields by an average of 2.2% compared to monocultures.[596] **Crop mixes also outperformed monocultures under both biotic** (e.g., pests, diseases) **and abiotic stresses** (e.g., heat, drought, limited soil mineralization), proving their higher ability to adapt to climate change.[597] A further review of 98 meta-analyses comparing diversified and uniform systems demonstrates that crop diversification enhances above- and below-ground biodiversity and ecosystem services (e.g., pollination, pest control, nutrient cycling, soil fertility, and water regulation) while stabilizing yields – with positive outcomes reported in two-thirds of cases.[598]

These systems also play an important role in conservation. While many seeds can be stored ex-situ for decades, in situ conservation (on-farm cultivation for conservation) allows for the continued evolution and adaptation to changing environments.[599] This "conservation through use" ensures continuous renewal of resilient and diverse crops, particularly for endangered varieties.[600,601]

In the Sikkim Himalaya region, local farming communities cultivate over 126 cereal landraces, 132 vegetable species, 38 spices, and 64 fruits.[602] In the Telangana State of southern India, peasant seed networks are growing and conserving over 80 landraces, including millet, bean, gram, and pea varieties.[603] The Shitoucheng Community seed bank in China now hosts over 100 varieties of crop seeds, including over 30 types of corn through farmer breeding efforts.[604] In Cameroon, the Concertation Nationale des Organisations Paysannes ("National Consultation of Farmers' Organizations") supports the conservation and cultivation of indigenous groundnut varieties through the use of traditional bottle-shaped granaries that help farmers effectively store seeds in their homes.[605]

Peasant seed systems are developing and adapting specific crop varieties for climate resilience.[606] For example, peasant farmers in Kerala, India, have developed drought- and disease-resistant pepper varieties through seed selection.[607] In Yunnan Province, China, the Naxi ethnic group have identified that local bean varieties can thrive in less fertile soil, providing a safeguard against increasing drought.[608] In Mexico, farming communities and campesino organizations grow over 59 maize landraces thanks to seed sharing and saving practices.[609] In Tunisia, peasant farmers are reviving Mahmoudi durum wheat, a drought-tolerant variety.[610] In the Philippines, the farmer-led network of peasants, NGOs, and scientists MASIPAG has collected more than 2,000 rice cultivars in the last 30 years, and identified 18 drought-tolerant, 12 flood-tolerant, 20 salt-water tolerant and 24 pest and disease tolerant varieties.[611]

Credit: Farmers' Seed Network (China)

ci Landraces refer to seeds that have co-evolved alongside local farming practices and environments. The FAO defines them as "dynamic population(s) of traditional crop varieties that have some, if not all, of the following characteristics: historical origin, distinct identity and lacks formal crop improvement, as well as often being genetically diverse, locally adapted and associated with cultural practices and associated with traditional farming systems." See Walter, S. (2021). The Legal Regimes Governing Seeds and the Future of Agriculture—Conservation, Access, and Ownership. Working Paper of the Global Restoration Project.

Peasant seed systems are also essential to weather climate shocks. For example, in Yaxcabá, Mexico, unusually heavy rains in 2012 severely reduced milpa cultivated areas (i.e., areas intercropping maize, beans, and squash) and crop diversity on ejido lands.[612] Yet by exchanging stored seeds within families, the wider community, and neighbouring villages the following year, farmers were able to quickly recover and restore crop diversity.[613] Similarly, in Northern Mali, a local farmer-managed cooperative spanning three villages ensured the availability of 10 million tonnes of high-quality local pearl millet seeds for farmers to buy during a major drought in 2006 that heavily depleted farmers' seed stocks.[614] The cooperative later supplied some 41 million tonnes of locally-adapted seeds to humanitarian relief agencies in 2018 for Malian farmers.

However, **as climate patterns shift and extreme climate events become more recurrent and severe, peasant systems may not be able to adapt as rapidly as required to develop adapted seeds and recover seed stocks.**[615] Seed quality, quantity, and contamination remain challenges in some peasant seed systems that communities are seeking to address through participatory quality assurance mechanisms, collaborations with small-scale breeders and research institutions (see more below), and improved selection and storage practices. For example, current efforts to improve traditional storage practices include the use of bioinputs (e.g., seed coating using naturally-occurring microbial inoculants or plant extracts), storing materials (e.g., to regulate moisture and airflow, deter pests, maintain seed viability), or community infrastructure to preserve seeds.[cii] In turn, the capacity of seeds to be stored using appropriate local storage methods has been found to be a central criterion in peasant seed selection and breeding.[ciii,616]

In a 2020 report, the WHO highlighted the role of biodiversity as a foundational pillar for health and nutrition.[617]

While studies on the role of seeds and seed systems in promoting nutritious diets are limited,[618] **the diversity of species and varieties nurtured by peasant seed systems, and peasant agroecology in particular, are often linked to positive health and nutrition outcomes.**[619,620,621] Through seed exchange and local markets, farmers and rural communities ensure year-round availability of healthy, tasty, and culturally-appropriate foods.[622] Farmers cultivating evolutionary populations of wheat in Iran, France, and Italy demonstrated that genetic crop diversity not only enhances yield stability and climate adaptation, but also improves dietary diversity and appeal (e.g., in the production of breads with greater aroma, flavor, and quality).[civ] The "Small Beans, Big Health" project, led by the Chinese Farmers' Seed Network, supports farmers in conserving and cultivating neglected native bean varieties to produce high-quality, flavorful beans and bean products that perpetuate local culinary traditions.[623]

Impacts on autonomy, knowledge, and control

Commercial seeds are consistently more expensive than farmers' seeds sold at local markets, and prohibitively costly compared to those that are shared, exchanged, and/or freely available seeds from previous harvests. In many low and middle-income countries, certified seeds (i.e., those that have gone through an official certification process) are 1.5 to 2 times more expensive than the price of grain.[624]

For example, one study in the Chimanimani district in Zimbabwe covering more than 200 households found that smallholder farmers considered 93% of the seeds from peasants systems affordable versus 32% to the agro-industry sees system.[625]

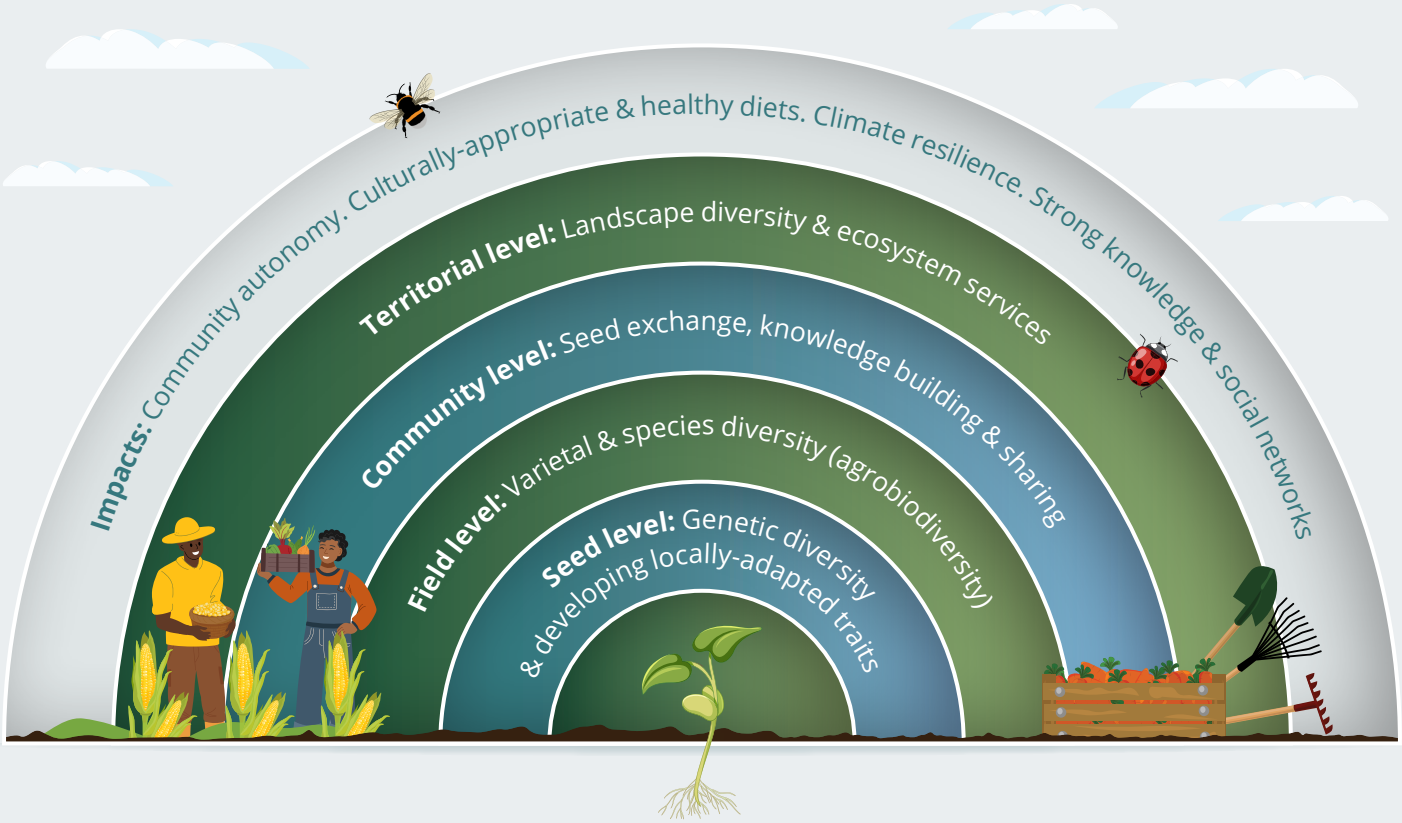
cii Storage tools and techniques include stacking of crops (e.g., for maize), using of pots or baskets made from various materials for long-term storage, burying crops in pits (e.g., for tubers), using traditional structures (e.g., trojes in Central and South America), using ashes or salt (e.g., for pigeon pea), or combining seeds with herbs or coating them in plant-derived products to protect seeds from pests and disease (e.g., Epazote).See AFSA. (2023). Seed sovereignty, a viable option for food and nutritional security in Africa.; Mobolade, A. J. et al. (2019). Traditional methods of food grains preservation and storage in Nigeria and India. Annals of Agricultural Sciences, 64(2), 196-205.; Winniefridah, M., & Manuku, M. (2013). Traditional science of seed and crop yield preservation: exploring the contributions of women to indigenous knowledge systems in Zimbabwe. International Journal of Humanities and Social Science, 3(4), 234-245.

ciii Seeds are often labeled with their origins and traits, bred to withstand long-term storage including moisture loss or freezing, and conserved both in situ (in fields) and ex situ (in storage), depending on community priorities. See for example, Théau, B. et al. (2021). Farmer Seeds for a Better Resilience to Climate Change - Collection of Best Practices. Initiatives Climat, GEF, SGP, UNDP, ARKANE, 4C Marocco; Atiah, D. B., & Alagidede, I. P. (2024). Toward a Political Economy of Indigenous Seed Systems and Climate Resilience in Ghana's Agricultural Renewal.

civ An evolutionary population refers to a mix of different varieties of the same species grown together to allow them to adapt to local environmental conditions over time.,

FIGURE 5

HOW PEASANT SEED SYSTEMS BUILD RESILIENCE & FOOD SOVEREIGNTY



However, not all small-scale farmers are able to produce and save their own seeds. Many lack access and control over land, or sufficient land to dedicate to seed production, while others face labour or time constraints required to save high-quality seeds.[626,627] As such, peasant seed systems play a crucial role in making seeds more accessible by enabling farmers to pool resources, knowledge, and labour.

Peasant seed systems can operate partially or fully outside of formal market systems,[628] through community seed banks, gardens, seed houses, granaries, or fairs, festivals, and local markets where seeds are bred, conserved, and shared. In Zimbabwe, for example, communities designate specific farmer seed breeders, allocate land for propagation, and collectively decide which varieties to maintain in fields and which to store in seed banks.[629]

Seed autonomy can also buffer against economic shocks and market volatility.[630] While commercial seeds are vulnerable to price volatility and market-induced shortages,[631] peasant seed systems provide more stable access to diverse, reliable, and context-appropriate seeds.[632] The importance of peasant seed systems has been particularly evident in times of crisis and uncertainty.

Community seeds banks and informal exchange also played a key role in ensuring access to seeds for many during the 2020 COVID-19 pandemic.[633,634] In Guatemala, Qachuu Aloom – a women-led organization cultivating and commercializing native and heirloom seeds – developed a mobile sales model to provide seeds to neighbouring villages when access to markets was limited during the pandemic.[635]

Communities of practice often arise from the exchange of knowledge and seeds. National and regional farmers networks such as COPAGEN in West Africa, Fecodesa in Nicaragua, the Indigenous Seed Keepers Network in the US, MASIPAG in the Philippines, Red de Semillas Libres in Spain, or Rete Semi Rurali in Italy are some of the many examples that provide space for seed exchange and storage, and knowledge exchange around the world.[636] These networks often benefit from collaborations with NGOs, universities, and research centers, through participatory research programs in particular, which remain crucial in contributing to local climate resilience. (See Box 15.)

BOX 15

PARTICIPATORY PLANT BREEDING

Participatory plant breeding (PPB) aims to improve crops through collaborations between farmers and agricultural scientists. PPB assumes equal partnerships between farmers and researchers, as well as the fair sharing of knowledge, expertise, and results (including new crops and seeds).[637] PPBs were developed in the late 1980s as a direct critique of Green Revolution breeding programs,[638] acting as a practical and a political response to the genetic erosion and centralization of knowledge of these programs. In 2019, an overview of PPB programs found that they have been used in over 69 countries (85% in the Global South) covering some 47 crops.[639]

PPBs involve intensive farmer participation in agenda setting, decision-making, identifying crops' key traits and benefits. This usually includes multi-location variety testing in farmers' fields in order to determine a crop's suitability, adaptability, storage quality, nutritional value, pest and disease resistance, agronomic performance, and more. In addition, farmers will not only evaluate the economic and agronomic viability of a new variety, but also its social and cultural relevance.

Studies demonstrate that varieties developed through well-designed PPBs are more likely to be adopted by farmers as they reflect their priorities and realities. Across Africa, where commercial seed systems are heavily promoted by foreign actors, PPBs provide the means for smallholders to co-create and cultivate new, accessible, and field-test hybrid and non-hybrid varieties.[640] In the Global North, one study found that 84% of the PPB programs in the US, Canada, and Europe were implemented to fill key research and breeding gaps for organic agriculture crops.[641] Examples of PPBs include:

- In **India**, civil society groups, seed breeders, and Adivasi farmers work together to conserve and share local rice varieties through community seed banks, exchanges, and farmer networks – working with public seed laboratories to assess their varieties and identify quality traits.[642]
- In **Guangxi Province, China**'s first participatory plant breeding (PPB) began in 2000 between farming communities, the Farmers' Seed Network and national research institutions. The effort led to the conservation and improvement of 27 local maize and vegetable varieties to improve their climate resilience, including the ability to withstand prolonged droughts, rising temperatures, and pest outbreaks.[643]
- In **France**, the Réseau des Semences Paysannes (Network of Peasant Seeds) participatory plant breeding initiatives are reviving landraces and heritage varieties lost in the industrialization of agriculture. Working groups organized by crop species are tasked with organizing workshops, trainings, farm visits, and seed exchanges – where researchers, agronomists, and technicians are invited to take part in these initiatives, as allies to these farmer-driven initiatives.[644]
- In **Latin America**, Comités de Investigación Agrícola Local (CIALs or Local Agricultural Research Committees) are farmer-led research services within rural communities who identify local problems and carry out research and experiments to find practical and context-adapted solutions. Some CIALs have focused specifically on participatory plant breeding research, such as in Honduras.[645]
- The **international network** and community of practice, Prolinnova, has also been rethinking the role of researchers altogether by promoting "farmer-led innovation development."[646] Its work has included participatory plant breeding projects, for example in northern Ethiopia, where women farmers and breeders developed barley varieties that are more nutritious and drought-resilient.[647]

Many of these initiatives are also challenging the modalities of farmer-research collaborations and are raising crucial questions about epistemic justice, i.e., whose knowledge is recognized, legitimized, and under what conditions it is shared.[648] Researchers, NGOs, and other actors are invited to *support*, rather than drive, research projects and experimentation, recognizing the role of farming and Indigenous communities as innovators in their own right and the ultimate decision-makers within agricultural systems. Collaborations can also encourage changes in the use of language to better reflect ways of thinking relevant to farmers and communities. For example, France's Réseau des Semences Paysannes mentions "on-farm maintenance and renewal of agrobiodiversity" rather than "the conservation and breeding of genetic resources".[649]

Importantly, **protecting peasant seed systems and traditional knowledge includes the right to refuse collaboration,** alongside defending farmers' rights to save, share, and propagate seeds.[650] Defining the nature and scope of partnerships is critical in a context in which many Indigenous and peasant seed keepers continue to highlight the ongoing impact of colonialism on seed systems and knowledge sharing; this includes experiencing negative interactions with public, private, and non-profit actors, including through appropriation of their knowledge, tokenized involvement in collaborations, and under-compensation for their time and capacity.[cv]

Loss of seed sovereignty and marginalization of peasant seed systems are also closely linked to rural women's rights. Privatization of seeds, land, and resources and appropriation of knowledge are undermining the role of women as knowledge holders and decision-makers in agriculture.[651] Yet the role of women in seed systems is also embedded in complex gendered dynamics shaped by patriarchal systems. In many communities around the world, men typically control income and commercial seed purchases, while women are responsible for food preparation and subsistence, selecting seeds from peers to ensure household food security.[652] These ongoing inequalities, exacerbated by colonial and postcolonial structures, also intersect with commercial breeding agendas, which tend to neglect so-called "low market value" crops that are often central to women's production systems, household nutrition, and community well-being.[653] (See Box 16 for more on women in seed systems.)

Credit: McKnight Foundation

cv In addition, elders who hold seed saving knowledge within their communities have noted challenges in intergenerational knowledge transmission, and the structural barriers (e.g., time, capacity, and lack of resources) required to support teaching and learning opportunities. See Davies, N., & Sovereign Seeds. (2024). Indigenous Seed Keeping and Seed Climate Adaptation. Sovereign Seeds.

BOX 16

WOMEN IN SEED SYSTEMS

Despite systemic inequalities, women continue to play a central role in maintaining community-driven seed efforts to ensure their own livelihoods, while upholding community and ecosystem resilience. Examples include:

- In the Andean highlands of **Ecuador**, women farmers maintain food sovereignty through "revolving seed banks," a two-for-one system where farmers return twice the amount of seeds they borrow, allowing the bank to continuously expand its reach. For example, a bank in Chirinche Bajo, Cotopaxi started with only 25 pounds of potato seed and has since enabled members to produce over 110,230 pounds of potatoes.[654]
- In **West Africa**, the 'Nous Sommes la Solution' (We are the Solution) movement unites over 800 women's associations and 185,000 members across Burkina Faso, Côte d'Ivoire, Ghana, Guinea, Mali, Senegal, The Gambia, and Guinea-Bissau. It promotes agroecology, food sovereignty, and the defense of traditional seed systems, working to support the vital role women in the region traditionally play in seed selection, storage, and exchange.[655]
- In Telangana, **India**, Sanghams (community groups) of marginalized Dalit and tribal women supported by the Deccan Development Society (DDS) have used community seed systems as a means to achieve agricultural autonomy. Local women manage seed banks across 60 villages,[656] supplying farmers with up to 80 traditional crop varieties.[657] The success of their approach has contributed to its replication beyond the region.[658]
- In **South Korea**, the Korean Women Peasants' Association (KWPA), operates across 15 cities and eight provinces, champions the critical role of halmeoni (grandmothers) in preserving crop diversity. The KWPA mobilizes cultural identity and food sovereignty to resist the homogenization of crop varieties. The network collects vital knowledge and traditional seeds from older peasant women, who maintained them on subsistence plots despite decades of national policy promoting industrial agriculture.[659]

Implication for power in food systems

Seed saving represents a complex set of practices that involves "planting, tending, selecting, harvesting, storing, eating and replanting of seeds [...] as well as processes of exchanging and knowledge-building".[660] The vast majority of farmers, local and Indigenous communities supply themselves with seeds through peasant and informal seed systems. Yet, evidence demonstrates that these same communities are the most severely affected by the privatization of seeds and the entrenchment of industrial agriculture, as their livelihoods most depend on their ability to save their own seeds.[661,662,663]

In other words, peasant seed systems continue to function despite highly adverse conditions. Beyond climate pressures, **peasant seed systems are under systemic threat – including criminalization and erasure – under current intellectual property regimes, regulatory frameworks, and national seed legislation.**

A number of approaches seek to move beyond intellectual property regimes and to identify governance frameworks that could more effectively protect farmers and communities from enclosure. Some social movements and activists around the world are reimagining seed governance through a commons framework.[664] Seed commons broadly refers to the collective management of seeds and related knowledge, and proposes an alternative vision of governance to corporate enclosure and the commodification of nature and social relationships.[665]

However, commons-based approaches are not universally agreed upon, and encompass a range of perspectives and practices. Many remain rooted in property-based language (e.g., "open source" licensing) to protect seeds from privatization. While these approaches aim to resist enclosure, they can reproduce ownership- or property-based models in aiming to defend the right to seeds, and could face practical challenges: as open licenses are rarely tracked, monitoring is weak, allowing violations to go unchecked. By contrast, rights-based approaches are being taken up by many Indigenous and peasant movements, and postcolonial activists (e.g., custodian or stewardship-based models). These approaches, including the collective right to seeds, frame seed governance through the lens of shared heritage and cultural rights.[666]

As discussed in Section 3.1, global trade and IP regimes continue to threaten the seed rights of communities around the world.[667] For example, under the UPOV Convention, seeds must meet strict criteria to be legally protected, including stability, distinctness, and uniformity. However, peasant seeds are constantly evolving to adapt to local conditions, and are thus unstable by nature, excluding them from legal protection and recognition.

Threats to peasant seed systems are also being met with resistance at all levels. In Colombia, Resolution 970 – introduced in 2010 to fulfill a bilateral trade agreement with the United States – banned farmers from saving or exchanging seeds that were not certified or registered by the Colombian Agricultural Institute (ICA).[668] This resolution led to the ICA seizing and destroying crops in farmers' fields before it was repealed following nationwide peasant strikes.[669] In Bénin, the 2019 *Benin sans UPOV campaign* ("Benin without UPOV") mobilized over 100,000 actors to reject the country's accession to UPOV and included efforts to strengthen national databases and public awareness on farmers' seeds.[670] In 2012, the *Asociación Nacional para el Fomento de la Agricultura Ecológica* (National Association for the Promotion of Organic Agriculture) led a decade-long battle against the "Monsanto Law" (Decree N.21-2012) that culminated in the Honduras Supreme Court striking down the law – making it one of the first rulings citing the UN Declaration on the Rights of Peasants (UNDROP) to defend sovereignty and the rights to dignity, adequate living, and culturally appropriate food.[671,672]

There are also a growing number of cases that demonstrate how **peasant seed systems and participatory plant breeding programs can influence institutional reform.**

In 2000, China's first PPB program faced early barriers to formal recognition and certification of the varieties it developed, as seed laws did not recognize collective intellectual property nor benefit-sharing. However, ongoing dialogue between farmers, researchers, and provincial and national policymakers fostered opportunities for mutual learning and reflection, leading to the recognition of PPBs as the seeds they produce as legitimate approaches to conventional crop improvement programs. In 2004, the Chinese Ministry of Agriculture incorporated PPBs into its reform programs and into national breeding strategies by 2008.[673]

As also noted in Section 3.1, international frameworks including UNDRIP and UNDROP have sought to redress farmers' and Indigenous People's rights to seeds. UNDROP, in particular, marked a turning point in human rights law by enshrining individual and collective rights of peasant and rural communities, granting them new rights including to seeds, land, and food sovereignty.[674] The Declaration also represents an unprecedented moment in international lawmaking, in which peasant and Indigenous movements played a prominent role in initiating, drafting, and negotiating the text.[675]

Ultimately, peasant seed systems are not merely an innovative form of seed saving, or knowledge exchanges, they are "quiet acts of activism."[676] They are social and ecological systems through which communities are not only ensuring climate resilience, but reaffirming their cultures, traditions, and identities. The struggle to maintain peasant seed systems is one of self-determination. Strengthening these systems requires recognizing the many benefits of peasant seed systems, as well as addressing the historical and structural pressures that threaten their survival.

Efforts are ongoing to develop governance models in policy and research that respect the agency and control of farmer and Indigenous communities over their seed systems, requiring support from breeders, researchers, scientists and policymakers alike. As described by Jean-Marie Koalga, President of the *Bon Samaritain* Association in Burkina Faso, "In our culture, we compare seeds to water: refusing seeds to someone is like refusing them life. Peasant seeds are our living heritage. They carry the past, support the present, and prepare the future of our communities."[677]

4

THE PATH AHEAD: INNOVATION FOR JUST AND SUSTAINABLE FOOD SYSTEMS

Credit: McKnight Foundation

Farmers, farmworkers, Indigenous Peoples, and local communities actively shape agricultural systems through their daily practices, knowledge, and labour. Yet innovation systems play a major role in shaping farming activities by impacting which tools, techniques, and practices are accessible to them. At their core, innovation systems hold the power to define and frame what counts as a problem, and what is recognized as a solution. They influence whether farmers and communities have agency to lead, choose, adapt, refuse, or govern different innovations, and determine whose knowledge is valued, who benefits from agricultural innovation, and how livelihoods are sustained.

Innovations and the narratives that surround them are deeply political. They reflect and reproduce particular social, cultural, ecological, economic, and political processes through which power relationships are shaped and negotiated. As shown throughout this report, **innovations tend to reinforce the system in which they are developed,** whether extractive or inclusionary, corporate-driven or farmer-led, industrial or place-based.

This section asks what kinds of innovation systems meaningfully support sustainable, equitable, and resilient food and agricultural systems. We begin with a synthesis of cross-cutting insights identified in Sections 1-3, based on the report's five innovation assessment criteria: 1) ecological sustainability, 2) equity, livelihoods, and labour, 3) autonomy and control, 4) knowledge and skills, and 5) implications for power in food systems. From this assessment, we identify key factors and conditions for innovation systems to support more just and sustainable food systems and provide recommendations for strengthening those systems.

Ecological sustainability. As the impacts of climate change intensify, sensitivity to place, scale, and context has become a critical consideration in agriculture. Our analysis found that **innovation systems that best support ecological sustainability focus on holistic approaches to farming** that are adapted to the local environment and work with ecological processes. They primarily rely on natural resources and ecological interactions, reducing (if not entirely removing) the need for chemical inputs (Section 2.2).

These systems are often underpinned by worldviews that understand humans and nature as part of a whole, fostering a combination of ecological, social, and technological innovations – such as ecological pest management practices or peasant seed systems – that foster agrobiodiversity and ecological resilience.

In certain instances, these systems are integrating digital tools, such as agricultural and weather data or platforms for knowledge sharing and exchange, to support farming practices. The information derived from these tools is proving particularly useful when triangulated with other forms of knowledge and data. Like all digital technologies, however, these tools rely on material infrastructure (e.g., energy, water, minerals, land) and labour, which should be recognized in assessing their full ecological and social costs.

By contrast, **innovation systems that limit ecological sustainability are characterized by an aim to optimize or fine-tune industrial agriculture practices through the use of specific technologies,** rather than challenge their underlying logic or the root causes of their negative impacts. They are underpinned by a vision of agriculture that separates human activity from ecological processes, prioritizing technologies that simplify, codify, and aim to control complex living systems. These innovation systems, particularly those that further and are furthered by precision agriculture and biotechnology, claim to address environmental challenges, but often do so by externalizing ecological costs. As shown in Section 1.1, and 1.3, and 3.3, the use of Big Data-driven tools, including precision tools and bioengineering, requires high energy and resource use and tends to lock farmers into increasingly resource-intensive production systems with harmful ecological impacts.

Equity, livelihoods, and labour. Farming undeniably includes physically and mentally demanding work, but many who work the land speak of it in terms of purpose, pride, connection, and care.[678,679,680,681] **Innovation systems that support equity recognize this complexity, and tend to aim to reduce physically and mentally harmful or repetitive work, while improving quality of life and maintaining the skills, knowledge, and meaning embedded in farm work.** Rather than aiming to reduce or eliminate farm labour, these systems develop social innovations such as collective labour-sharing arrangements, ecological innovations to reduce exposure to agrochemical toxins, or technological innovations around safer, more efficient, better adapted, or less repetitive tool use. Women's knowledge and labour play a central role in these systems, particularly in seed saving and breeding (Section 3.2) or in soil and crop management on smallholder systems (Section 1.2 and 2.2), though it often remains undervalued. These systems develop innovations to support farmers and communities to remain on the land, strengthen local economies, and value farm labour.

By contrast, **innovation systems that hinder equity are largely oriented towards reducing labour costs through capital-intensive technologies,** particularly through precision tools and automation. These systems are based on aspirations of "modern" societies, where only a minority of people farm. As shown in Sections 1.1 and 1.2, these systems frame agricultural labour as inherently "drudgerous" in order to justify highly automated and costly tools primarily available to and adopted by large-scale industrial farmers – predominantly operated by men in high-income countries. Yet, our analysis confirms these trends risk reinforcing inequalities by increasing precarious labour and poor working conditions on the farm,[682] while displacing labour and obscuring exploitation elsewhere (e.g., AI data trainers, miners extracting critical minerals).

More broadly, our findings highlight that labour shortages in agriculture often stem from structural issues including inadequate wages and poor working conditions, job instability, criminalizing migrant labor, limited access to land and succession planning, or lack of training and support – issues that automated and precision tools are likely to exacerbate.[683] In addition, technologies introduced to reduce physical strain or improve efficiency can sometimes become the very same technologies that eliminate jobs, deskill workers, and shift control away from farmers and farmworkers. More collective reflection is therefore needed to address these tensions and precarious labour conditions – particularly for women, migrant workers, and minority groups – and build out conditions that could support dignity, recognition, and meaningful livelihoods for all who work the land.[684]

Autonomy and control. Innovation systems that support farmers' autonomy and control tend to be decentralized and place-based. Our report highlights that these innovation systems aim to expand farmers' capacity to decide when, whether, how, and with whom to innovate. They tend to prioritize innovations that are accessible, affordable, adaptable, and repairable – often operating partially or entirely outside proprietary regimes (e.g., commons, gift economies, open-source models). In these systems, autonomy is not necessarily framed as an individual choice, but mainly through collective control and self-determination. (See Box 17 for reflections on the role of digital tools in these systems.)

Innovation systems that impede farmers' autonomy and control are characterized by centralized decision-making structures and proprietary rights concentrated in the hands of a few corporations. As shown in Sections 1.1, 2.1, and 3.1, corporate-led innovation pathways heavily rely on intellectual property regimes to function, giving a narrow set of actors power over data, algorithms, machinery, and even genetic material. In these systems, autonomy and control remain unevenly distributed and contested, as farmers' and communities' choices are systematically constrained – with implications for data ownership and privacy, surveillance, control over seeds and plant resources, and the rights to repair and adapt technologies.[cvi]

Our analysis also shows that the transformation of farming knowledge into standardized, digitized information, and the assetization of that data have become the backbone of corporate-led agricultural innovation systems – and industrial agriculture more broadly. Enabled by a small number of proprietary platforms, these systems are presented as expanding farmers' choice by giving them increased access to information. Yet the precision tools and gene-editing technologies these systems depend on more often create the illusion of choice, locking farmers onto technological treadmills through contractual agreements, technological packages, or market structures that require continuous investment and deepen dependence on external actors and inputs.

cvi These dynamics are also extending beyond the farm with similar risks across the entire food chain. In particular, blockchain technology for product tracing (e.g., IBM's Food Trust) is being developed as a further means for major agrifood businesses and tech providers to oversee – and consolidate control over – farmers, suppliers, and/or processors under the guise of greater transparency. For example, Walmart has asked that all their leafy green suppliers join IBM's Food Trust to ensure traceability in case of a recall. IBM's Food Trust is being used and tested by big food corporations, but these are more downstream so listed here: Dole, Driscoll's, Golden State Foods, Kroger, McCormick and Company, McLane Company, Nestlé, Tyson Foods, Unilever and Walmart, & more recently Carrefour. Also been used by olive oil producers.

BOX 17

REFLECTIONS ON DIGITAL TECHNOLOGIES, AUTONOMY AND CONTROL

Many digital tools have been co-developed with or designed by farmers to support farming practices, knowledge exchange and communication. Examples include Access Agriculture's agroecological and organic farming training videos made by farmers and shared on a digital library which can be browsed through thanks to an AI chatbot,[685] or open-source apps such as FarmOS, LiteFarm, or Ugunduzi co-developed by researchers, grassroots organizations, and farmer networks to support small-scale and agroecological farming.[686] Digital tools are also increasingly used to strengthen territorial markets, such as apps to connect farmers with local markets.[687] In these cases, digital tools tend to be accessible, locally governed, respectful of digital sovereignty, and complementary to – rather than displacing – agroecological practices. However, some digital tools designed for small-scale farmers, such as AI-driven decision-making including Digital Green (an AI extension platform in India and Microsoft spinoff)[688]or Plant Village Nuru (CGIAR's AI assistant for farmers in India, Kenya, and Tanzania),[689] may externalize decision-making and move power away from farmers, with little to no mechanisms of accountability from these apps if their advice is flawed.

Lingering tensions also stem from the infrastructure underpinning some digital tools. Many digital projects designed for and by farmers and local communities remain dependent on Big Tech infrastructures – particularly those reliant on cloud services – limiting the extent to which these technologies can truly be controlled, governed, and led by farmers. At the same time, publicly-run alternatives are often less efficient, project-based (thus struggling to last beyond project timelines), or underfunded.[690] In addition, tech developers and NGOs developing "closed" AI tools for smallholder farmers (i.e., digital technologies that do not rely on external cloud services) can be less reliable and ultimately less useful than agribusiness' platforms with larger budgets to spend on optimizing digital tools.

These issues invite us to consider the conditions under which digital tools could be developed and used to strengthen, rather than compromise place-based autonomy, knowledge, and control. Answering this question may require identifying conditions and parameters for their design, use, and control that go beyond technical compatibility, and calling for democratic processes that include those most affected by these technologies.[691] These considerations also underscore that digitalization should always be the result of a voluntary choice rather than a prerequisite in today's farming systems.[692] And although reflections around the compatibility of digital tools with sustainable and equitable food systems are needed, they should not contribute to further skewing public and private funding away from non-digital innovations.

Knowledge and skills. Innovation systems that support farmers' knowledge and skills are grounded in plurality (of Indigenous, peasant, and/or scientific knowledges), place, and collective learning. They value and recognize farmers, Indigenous Peoples, and local communities as knowledge-holders and innovators in their own right, building on generations of culture, practice, observation, and experimentation.[693,694]

As shown throughout the report, knowledge and learning in these systems center around consented sharing, reciprocity, and creativity, building practical skills and knowledge that support farmers and communities in developing and adapting innovations most relevant to them, from practical tools to locally-adapted seed varieties. (See Box 18 for the role of research and academia in these innovation systems).

Innovation systems that impede farmers' knowledge and skills tend to privilege top-down, standardized, scalable, digitally data-driven, and codified knowledge (i.e., technoscientific knowledge) **over embodied or experiential understandings.** Farmers' participation in these innovation processes is often absent or limited to data provisioning or consultation in later stages of development, rather than meaningful involvement to shape priorities and outcomes. In some cases, these systems may even appropriate peasant and Indigenous knowledge for commercial purposes without free, prior, or informed consent or equitable benefit-sharing, as illustrated in cases of biopiracy around seeds and plant genetic resources in Section 3. Lastly, the technical complexity of some digital and biotechnological technologies promoted by these innovation systems deepens dependencies on external expertise.

Our analysis also highlights that ongoing tensions remain on participation in knowledge production. While farmer participation in innovation is often invoked in agricultural innovation systems, its meaning varies greatly, from more extractive consultations to fully farmer-led processes. At its core, participation in innovation processes is about democratizing how innovations are imagined, designed, disseminated, and contested.[695] Yet participation alone does not guarantee relevance for farming, Indigenous, and local communities even with the best intentions, nor do these communities always want or have the capacity to participate – especially when involvement in research and knowledge collaborations entail lengthy time commitments or loss of income (due to the time required).[696]

BOX 18

THE ROLE OF RESEARCH AND ACADEMIA IN AGRICULTURAL KNOWLEDGE SYSTEMS

Academic and research institutions can play different roles in agricultural innovation systems. While researchers increasingly aim to include farmers in their work, academic knowledge production is rooted in colonial, patriarchal, and capitalist structures, and these long-lasting dynamics have led some participatory initiatives to fall short of their intentions.[697] Many scientific institutions have contributed to, and continue to, eradicating and marginalizing peasant and Indigenous Peoples' knowledge. This marginalization occurs in multiple and interconnected ways, including disciplinary traditions like international development studies that have historically privileged Western knowledge systems over peasant and Indigenous ones, universities which largely exclude peasant and Indigenous knowledge from their curriculum, and research being conducted on Indigenous Peoples and peasants without their consent.[698,699]

However, many scholars also work to shift agricultural research towards more participatory and pluralistic approaches,[700] with important work already underway to rethink the role of academic institutions and research organizations in supporting farming and Indigenous communities, food sovereignty, and agroecological movements. Initiatives like Prolinnova train academics to document peasant innovations and offer support only as farmers request, while the Institute for Agroecology at the University of Vermont actively engages with farmers, Indigenous Peoples, and social movements to address food system challenges and advance participatory research practices.[701] The third Nyeleni Forum gathered hundreds of people – including peasants, farmworkers, Indigenous people, fisherfolk, pastoralists, trade unions, philanthropies, civil society organisations, and scholars – to foster critical reflection around systemic transformation, and, among other topics, provided a space for ongoing reflection on researchers' engagement with social movements. These many examples highlight that academic engagement can help to strengthen farmer- and community-led knowledge systems, particularly when embedded in accountability, adherence to responsible research and innovation principles (RRI),[cvii] consent, and the right to refuse collaboration.

cvii Responsible Research Innovation is guided by the "anticipation, inclusion, reflexivity, and responsiveness" (AIRR) framework to develop and assess innovations. This framework calls for multiple continuous processes to anticipate and mitigate unintended consequences, inclusivity of all relevant actors in decision-making, reflexivity among researchers on the drivers of their work, and responsiveness to societal needs understood as the adaptability to reorient research pathways depending on new knowledge or conditions. See for example, Eastwood, C., Klerkx, L., Ayre, M., & Dela Rue, B. (2019). Managing socio-ethical challenges in the development of smart farming: from a fragmented to a comprehensive approach for responsible research and innovation. Journal of agricultural and environmental ethics, 32(5), 741-768.

Implications for power in food systems.

Innovation systems that help to distribute power more equitably are those shaped by decentralization. These systems aim to foster dignity, cohesion, and self-determination over how food is produced and distributed. They do not place the full burden of innovation on local communities alone, but couple grassroots innovation with the work of researchers, NGOS, and/or responsible technological developers, engineers, and designers to drive resilient, appropriate, accessible, context-specific agricultural innovation.[cviii] As climate, economic, and geopolitical instability intensifies, innovation systems based on place-based and adaptive governance are proving crucial to ensure equitable and sustainable food systems. Yet these systems remain systematically undervalued, undersupported, and sidelined by policies, regulations, and investments that favor corporate-led innovation pathways.

By contrast, **innovation systems that concentrate power are shaped by corporate consolidation across the agrifood and digital sectors, allowing companies to shape markets, technological pathways, and policies to their advantage.**[702] As shown throughout the report, these systems are promoted by corporate actors, but crucially supported by private foundations, governments, and international institutions through funding priorities, patent laws, seed and biosafety regulations, agricultural subsidies, and trade and competition rules.[703,704] Despite claims of inclusivity, corporate-driven innovation systems risk further marginalizing peasant, Indigenous, and women farmers and farmworkers, raising barriers for young people aspiring to farm, and sidelining social and political processes seeking to address structural issues, including on access to land and livelihood, autonomy, and self-determination.[705]

Corporate-led digitalization is also becoming central in the governance of food and innovation systems. As Big Tech companies own crucial parts of the infrastructure required for cloud-based digital tools, engaging with them becomes increasingly unavoidable for farmers, startups, and even public institutions, including national ministries and UN agencies such as FAO.[706] Moreover, digitalization is opening new avenues for mergers and acquisitions across agricultural sectors, creating further concentrated information supply chains.

Corporate-led pathways also reinforce colonial processes of imposition on and extraction from the Global South by the Global North.[707] While raw materials required for digital technologies are mainly provided by the Global South, AI systems in the region remain highly reliant on foreign providers and offshore data centers. At the same time, new disparities within the Global South emerge as some countries attract large new investments for agricultural digitalization (e.g., Kenya, Senegal)[708] relative to others. Lastly, the rush to develop AI infrastructure in the Global South also raises concerns over the influence of external actors on government agendas. For example, the African Union's new AI Continental Strategy[709] has been criticized for being heavily influenced by foreign tech lobbyists and for its lack of attention to the priorities of member states and local communities.[710]

cviii While we have focused on agricultural innovations in this report, a wealth of other social innovations exists to connect farmers to markets and alternative procurement networks, including Participatory Guarantee Systems of Alternative Food Networks (AFNs), or to improve community storage and processing. See for example, Castaño Hernández, L.M. (2023). Expanded seeds: Exploring local market dynamics in Latin America and the Caribbean. Groundswell International.

RECOMMENDATIONS: HOW TO BUILD OUT THE INNOVATION SYSTEMS TO BUILD JUST AND SUSTAINABLE FOOD SYSTEMS

To ensure innovation systems serve more just, resilient, and equitable agricultural systems, a first step is to shift the focus away from narrow techno- or innovation-fixes that distract from deep, systemic political transformation. **Innovations are needed but only when they emerge from and support the structural transformation required to build just and sustainable food systems.**

This transformation requires farmers, Indigenous, and community-based knowledge to gain greater recognition and institutional support. **It means talking about, funding, and governing innovations differently** to ensure they benefit communities and ecosystems. Innovations should stem from farmer, local, and Indigenous communities' needs, serving justice, sustainability, and sovereignty – not deepen corporate dependency and extractivism.

This transformation requires pushing back against the corporate-driven pathways that narrow the imagination and possibility of what innovation can be in both public and private sectors, and across civil society. It requires investing in farmer- and community-led approaches, along with public research, that value diverse ways of knowing and ensuring that communities retain control over the innovations that shape their livelihood (and in the case of digital tools, over the data and platforms that mediate them). A wealth of farmer- and community-led innovations have been highlighted in this report to draw inspiration from, and many others exist.

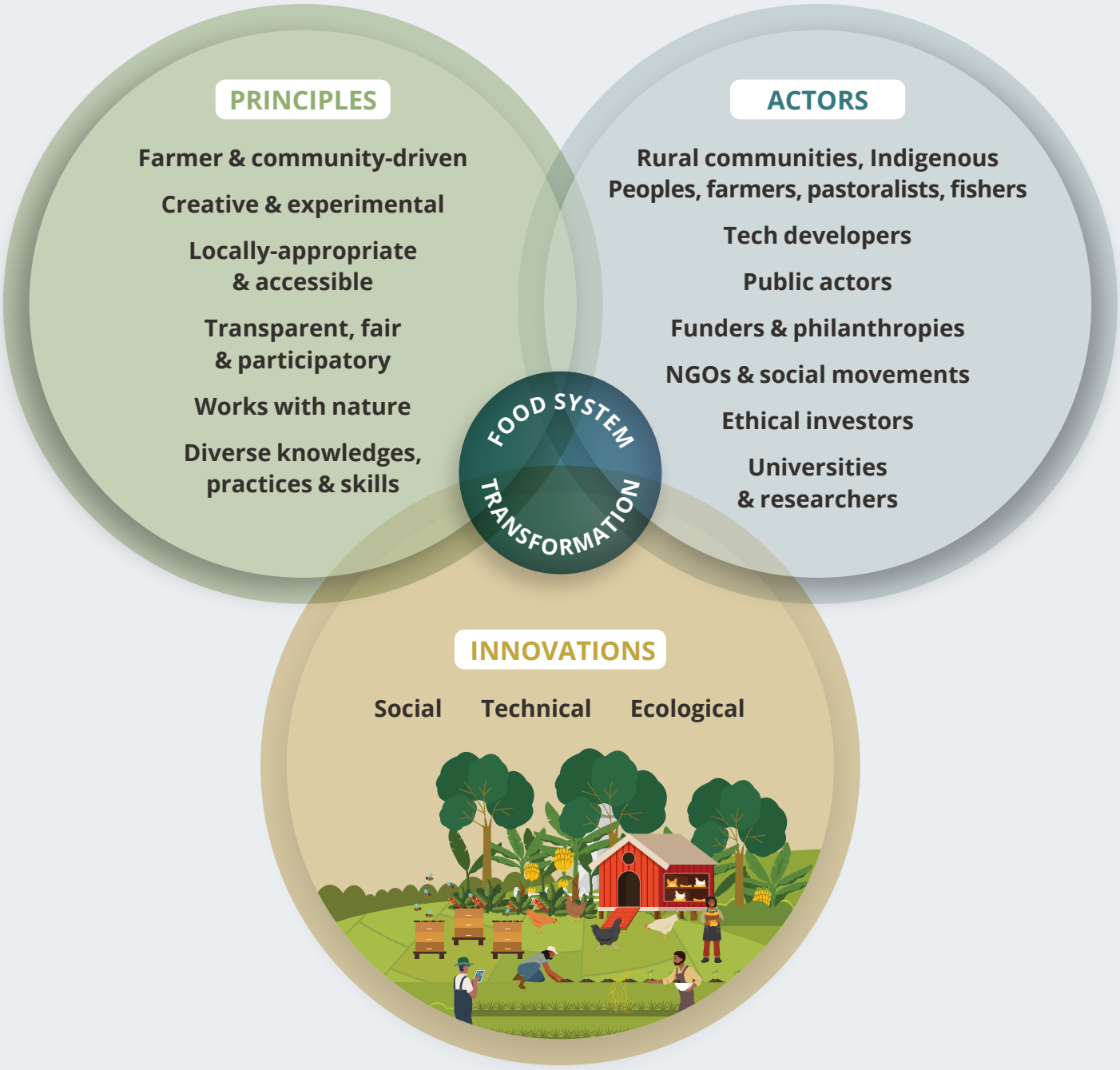
Building on existing frameworks and from our analysis above, the innovations systems we need must:

- **Recognize farmer, Indigenous & local communities as custodians and innovators,** and their control over the design, implement, and use of innovations and innovation processes;[cix]
- **Work with nature;**
- **Foster diversity** (of ecosystems and peoples, as well as knowledges, practices, and skills);
- **Remain locally grounded, appropriate, accessible, and inclusive;**
- **Nurture different knowledges, practices & skills**
- **Value creativity, experimentation, and learning;**
- **Prioritize dignity and autonomy of those who work the land,** and support their livelihoods;
- **Be based on transparent, fair, and participatory decision-making.**

cix Beyond the frameworks and treaties highlighted throughout the report, a number of international institutions are already working to recognize the role of smallholders, women farmers, and Indigenous communities in agricultural innovations. See, FAO. (2025). Bringing women innovators to the fore: Engaging in gender-responsive, farmer-led innovation and research; World Food Programme. (2021.) Smallholder Farmers.

FIGURE 6

INNOVATION SYSTEMS FOR JUST AND SUSTAINABLE FOOD SYSTEMS



Innovation systems for just and sustainable food systems will also require the involvement of a broad range of actors, including:

- **Rural communities, Indigenous Peoples, peasant farmers, farmers, pastoralists, and fisherfolk** as active creators, designers, adapters and evaluators of innovation;
- **Public institutions** (local/regional/national governments) to create enabling environments and build infrastructure systems to support diverse (digital and non-digital) innovation;
- **NGOs and social movements** at local and regional levels, as facilitators of innovation or knowledge sharing processes with small farmers and local communities;
- **Universities and researchers** to foster and advocate for transdisciplinarity, value diversity of knowledge, engage in co-innovation with farmers, develop and help validate and disseminate accessible innovations, and embed inter- and transdisciplinary approaches into curricula and research programs;
- **Tech developers and tech companies for the public good** to help advance reparable and accessible technologies aligned with data sovereignty and agroecological values (e.g., open-source) and to reorient design away extraction and explore social business models;
- **Ethical investors** (pension funds, social impact investors, "green investment" funds, sovereign wealth funds) to redirect finance away from agribusiness & towards agroecological initiatives and infrastructure, redefine the metrics used to assess positive impact, and align risk frameworks with agroecological practices;
- **Funders & philanthropy** to fund more experimental, long-view, and justice-centered innovation. For example, drawing on precedents set by Solidarity Philanthropy;[711]
- **Allies from related movements** and intersecting struggles from digital rights, labour, energy, food sovereignty, etc. For example, drawing on the efforts carried by the Nyeleni International Movement for Food Sovereignty and the recent Kandy Declaration for systems transformation.[712]

Bringing together these actors and principles, we outline four sets of recommendations to enable innovation systems we need. Some of these shifts may be challenging, given the scale of public and private resources currently directed towards industrial agriculture and corporate-driven models. However, these actions are interconnected, and collectively, can ensure meaningful and lasting change.

1 Strengthen public policy frameworks for responsible and just innovation

- **Protect and place the rights of Indigenous Peoples, local communities, farmers and farmworkers** at the heart of innovation development and food system transformation, ensuring their individual and collective rights to knowledge and genetic resources, based on UNDROP and UNDRIP (e.g. for seed rights, rights to land, knowledge rights);
- **Uphold Free, Prior, Informed Consent (FPIC) of Indigenous Peoples, local communities, and farmers,** including the right to recall, refuse, or withdraw from the use of technologies that have negative and/or unanticipated side effects, and mechanisms to archive and restore technologies displaced by new innovations;
- **Reframe national and international policy agendas to align with needs-driven and context-specific innovation development;**[cx]
- **Ensure fair income and decent livelihoods for farmers and farmworkers,** including remuneration for ecosystem services provided, access to land and secure land tenure, and financial support so that participation in farmer-led and other participatory innovation processes is possible and a genuine choice.[cxi] This also requires addressing more complex structural inequalities around class, gender, or landlessness that can shape who carries the labour and burden of innovation choices;

cx For example, by promoting a diversity of innovation pathways, involving affected actors in research funding decisions and developing accountability mechanisms in the governance of science, technology and innovation, as per the recommendations from STRINGS. (2022). Changing Directions: Steering science, technology and innovation towards the Sustainable Development Goals.

cxi For example, in 2014, under the "Loi d'avenir pour l'agriculture," France created a new legal status recognizing and supporting farmer collectives implementing, experimenting or sharing agroecological and sustainable farming practices. This legal status provides the groups with preferential funding or finance for specific projects. Ministère de l'Économie, des Finances et de la Souveraineté industrielle et numérique. (2025). Rapport annuel de performances: Annexe a projet de loi relative aux résultats de la gestion et portant approbation des comptes de l'année 2024. Développement agricole et rural. Assemblée nationale.

- **Rebuild public agriculture & extension service systems** to facilitate local experimentation and co-learning, and include agroecological approaches in their programs;
- **Embed data justice into food systems' digital governance,** building on existing frameworks (e.g., rights-based and structural data justice, CARE Principles for Indigenous Data Governance),[713] approaches (e.g. Māori Data Sovereignty),[714] and international recommendations (e.g., the Committee on World Food Security's Data collection and analysis tools for food security and nutrition);[cxii]
- **Establish clearer definitions and protections of public and private** (e.g., farmer data) agricultural data to safeguard farmer rights and collective rights, and prevent appropriation and misuses;[715,716]
- **Explore new and support existing digital commons-based and cooperative** models to ensure data is a public good (e.g., data trusts, data cooperatives,[717] national or regional digital commons frameworks, open-source digital tools and platforms),[718] supported by regulatory frameworks, long-term public investment, and the democratic oversight needed to support these more equitable and accountable models;
- **Establish rights-based governance aligned with international agreements** (e.g., UNDROP, UNDRIP, Nagoya Protocol) **for the collection, storage, access, and use of genetic and biological material and data** – including digital sequence information – to ensure transparent oversight of public and private databases; uphold countries' sovereign rights over genetic resources; and protect the rights of farmers, Indigenous Peoples, and local communities who nurture these resources, including by guaranteeing fair and equitable benefit-sharing.

2 Channel public and private funding and research towards sustainable, bottom-up initiatives

- **Reorient funding and research that align with Responsible Research and Innovation principles (RRI),** prioritizing participatory, farmer- and community-led innovation processes, including social innovations and horizontal networks that enable collective experimentation and mutual learning (e.g., farmer-to-farmer exchanges, farmer and grassroot innovation networks,[719] tool and seed libraries);
- **Create dedicated funds for farmer- and community-led innovation and knowledge sharing**[720] drawing from solidarity philanthropy and long-term funding models including Float[721] and the ADOPT fund.[722]
- **Redirect national and international development finance** away from programs that focus solely on top-down digitalization towards bottom-up social, ecological, and technological innovation systems, including redirection of agricultural subsidies;
- **Invest in public physical infrastructure** for bottom-up innovations (e.g., public seed banks, local food processing facilities, tool-making workshop), including digital public infrastructure (e.g., broadband, open repositories, public data centers).[cxiii] This must be accompanied by measures to strengthen short supply chains to improve farmers' access to local and territorial markets essential to ensuring farmer-driven innovations translate into viable livelihoods and resilient local economies.

cxii See the policy recommendations from the CFS and the limitations of the recommendations according to the Civil Society and Indigenous Peoples' Mechanism working group on data: Data.

cxiii See for example, how the US State of California is exploring the possibility of public computing infrastructure. McCarty Carino, M. (2025, 13 October). California explores possibility of public GPU infrastructure. See also lessons learned from India on the need for DPI to be aimed at public value maximization, be transparent and underpinned by social accountability mechanisms, support people's collective stewardship of the digital realm, be accessible to all, and ensure socialization of data dividends. IT for Change. (2025). Recovering the 'Public' in India's Digital Public Infrastructure Strategy.

3 Break up the power of Big Tech and Big Ag

- **Enforce and expand antitrust regulations and anti-merger laws** in the agrifood and technology sectors to reduce corporate concentration, which enables dominant firms to shape technological pathways and influence policy outcomes in favour of corporate-led innovation;[723]
- **Reform intellectual property rights** (IPR) on seeds,[cxiv] machinery, (bio)digital tools, algorithms, platforms, data,[724] and information to prevent enclosure and reduce market concentration. This includes curbing the use of patents and licenses to restrict breeding, repair,[725] or interoperability, and ensuring publicly funded innovation remains openly accessible.
- **Divest public funding from private research and re-invest public R&D for the public good,** ensuring accountability and role of different actors in science and innovation governance. This includes strengthening oversight of private funding in universities and public research institutions, through stronger conflict of interest disclosure, transparency requirements, and safeguards to ensure research agendas and outcomes are not driven by corporate interests;
- **Invest in transparent technological assessment processes and inclusive horizon scanning** to anticipate and respond to emerging risks and changes in the agritech landscape (including the precautionary principle and the right to refuse a technology).[726] This includes taking a broad approach to technological assessment based on social, ecological, and equity criteria, not only productivity or efficiency criteria.[727] It also requires critically assessing the full environmental impact and energy intensity of technologies and design technologies based on sustainability principles.[cxv,728]

4 Change the narrative on innovation

- **Recognize that innovation and innovation narratives are always political, shaped by specific actors, interests, and worldviews.** This includes acknowledging innovation can be social, ecological, and/or technological, and requires care, time, creativity and experimentation;
- **Expose the limits of 'technofix' narratives** (e.g., around precision agriculture, bioengineering), which frame political and social issues solely as technical problems.
- Make a clearer distinction in public discourse between **corporate-driven digitalization or digital agriculture** and **digital tools that could support agroecological transitions** when developed under the right conditions;
- **Use food system transformation narratives that go beyond innovation imperatives,** or use "innovation" and narratives with caution and awareness of the colonial and capitalist dynamics they risk reproducing.

Peasant and Indigenous practices embrace complexity, uncertainty, and the unpredictability of living systems – realities that cannot be captured by data and algorithms. When innovation begins with people and the land, rather than the data being processed on the Cloud, different agricultural futures become imaginable.

Creating fairer tools, technologies, and practices requires working with and through radically different ontologies – i.e., ways of living. Participation must go beyond approaches defined by Western, modernist, and colonial lenses. Accounting for structural biases and decolonizing innovation systems and the structures that underpin them will require deep, difficult, uncomfortable, but much-needed, work.

cxiv For example, in India, the 2001 Protection of Plant Varieties and Farmers Rights Act protects plant and seed varieties and breeders' rights as well as peasants' rights to save, use, sow, re-sow, exchange, share and sell farm produce. The African Union developed an African Model Law for the Protection of the Rights of Local Communities, Farmers and Breeders, and for the Regulation of Access to Biological Resources, with similar provisions. See Golay, C. (2020). The Right To Seeds And Intellectual Property Rights

cxv Several regional initiatives already serve as useful precedents for inclusive and comprehensive technological assessment. Bringing together civil society groups, NGOs, farmers movements, initiatives include the Africa Technology Assessment Platform (AfriTAP) coordinated by the African Centre for Biodiversity, Red TECLA (Red Latinoamericana de Evaluación de Tecnologías) in Latin America, and the Technology Assessment Platform Asia-Pacific (TAP-AP). See Assess Technology.

The intricate networks of life underpinning agricultural systems call for humility from scientists, tech developers, and institutions, and a rejection of dominant techno-solutionist logics.[729] This will mean continuing to push back against the assumption that innovation systems are "neutral". Fear of being labeled "anti-tech" or "anti-innovation" should not prevent the food movement from critically engaging with – and, where necessary, collectively refusing – technologies that may undermine their core values and existence. This potential act of refusal may sometimes even be necessary to create the possibility for the diversity of practices required to ensure just and sustainable food systems change.[730]

Resilience will not emerge from centralized, data-intensive industrial farming models, even less so in a context of the hollowing out of public services. It will come from the strategies, practices, and techniques occurring on the ground rooted in solidarity, reciprocity, and care. We see these spaces in peasant seed networks, collective tool-making initiatives, farmer-to farmer learning exchanges, and participatory agroecological processes taking shape around the world that require deeper support and acknowledgement as innovations in their own right.

FIGURE 7

CULTIVATING INNOVATION FROM THE GROUND UP

CONCLUSIONS

1. **Innovation is political.**
2. **Big Tech is a risky bet**. Corporate-led digitalization of agriculture deepens dependency, inequity, and ecological harm.
3. **Farmers and communities are pioneering real innovations from the ground up** benefiting ecology, resilience, and local economies – but these remain overlooked and underfunded.
4. **We must reclaim innovation** to work with nature, support dignified livelihoods, centre farmer autonomy, value diverse knowledge, and shift power away from corporate control.

RECOMMENDATIONS

1. **Strengthen public policy for just and responsible innovation.**
2. **Redirect research and funding to bottom-up, sustainable initiatives.**
3. **Break up the power of Big Tech and Big Ag.**
4. **Change the narrative on innovation.**

ENDNOTES

[1] See AGUAPAN.

[2] See l'Atelier Paysan and Fabriek Paysanne.

[3] See Farmers' Seed Network.

[4] World Food Prize (2025). Hunger's tipping point: an urgent call to transform food and nutrition security.

[5] Alexandrova-Stefanova, N. et al. (2023). Harvesting change: Harnessing emerging technologies and innovations for agrifood systems transformation – Global foresight synthesis report. Rome. FAO and CIRAD.

[6] For broader trends on how private actors (and especially major tech companies) are steering green transition narratives, see: Rikap, C., & Weko, S. (2025). A green transition orchestrated from Big Tech clouds? Globalizations, 1–20.

[7] See FAO. (2024). The role of innovation and digitalization in the sustainable use of natural resources to accelerate the implementation of climate-resilient and low-emission pathways in agrifood systems. FAO regional conference for Europe; Kovacic, Z., García Casañas, C., Argüelles, L., Yáñez Serrano, P., Ribera-Fumaz, R., Prause, L., & March, H. (2024). The twin green and digital transition: High-level policy or science fiction?. Environment and Planning E: Nature and Space; Javaid, M., Haleem, A., Singh, R. P. & Suman, R. (2022). Enhancing smart farming through the applications of Agriculture 4.0 technologies. International Journal of Intelligent Networks, 3, 150-164.

[8] See for example, African Union (2020), The digital transformation strategy for Africa (2020-2030); European Union (2022), The New European Innovation Agenda.

[9] World Bank. (2022, October 3). Transforming Agriculture and Food Systems through Data-driven Digital Agriculture: Learning from Practitioners.

[10] EU Commission. (2023, April 5). Digitalisation of the European Agricultural Sector: Activities in Horizon 2020.

[11] See Delanty, G., & Harris, N. (2021). Critical theory and the question of technology: The Frankfurt School revisited. Thesis Eleven, 166(1), 88-108; A Growing Culture & ETC Group. (2023). Politics of Technology; Klerkx, L., & Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?. Global Food Security, 24, 100347; Arora, S., Van Dyck, B., Sharma, D., & Stirling, A. (2020). Control, care, and conviviality in the politics of technology for sustainability. Sustainability: Science, Practice and Policy, 16(1), 247-262.

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[14] Rose, D.C., Barkemeyer, A., de Boon, A. et al. (2023). The old, the new, or the old made new? Everyday counter-narratives of the so-called fourth agricultural revolution. Agric Hum Values 40, 423–439.

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[17] Clapp, J. (2025). Titans of Industrial Agriculture: How a Few Giant Corporations Came to Dominate the Farm Sector and Why It Matters. MIT Press. p.279.

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