

QUALITY SEEDS, IMPROVED VARIETIES

The Economics of Crop Genetic Improvement and Farmer Uptake

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Key messages

- Crop genetic improvement has greatly enhanced agricultural productivity, food security, and economic opportunities for smallholder farmers globally. CGIAR has contributed significantly to efforts of national partners to develop high-yielding, stress-resistant, and nutritionally improved crop varieties.
- Early policy analyses, largely informed by the successes of the Green Revolution, documented substantial gains in agricultural productivity, income generation, and poverty alleviation. However, subsequent research highlighted persistent adoption challenges, including slow varietal turnover and seed replacement, which have been linked to diverse institutional constraints (such as weak extension systems), economic barriers (high seed prices, liquidity constraints), and behavioral factors (risk aversion, limited farmer knowledge).
- Initial crop improvement programs focused primarily on maximizing yields. Over time, programs have shifted toward prioritizing multidimensional traits, including tolerance to abiotic stresses (such as drought and heat), resistance to pests and diseases, enhanced nutrient use efficiency, nutritional quality (biofortification), and consumer- and market-preferred characteristics, to more effectively address challenges such as climate change and changing diets.

Looking to the future, research and policy recommendations should focus on:

- **Strategically bundling improved crop varieties with complementary inputs and services**—such as agricultural advisories, credit, insurance,

fertilizer, and guaranteed market access—to help overcome multiple simultaneous adoption constraints. Developing evidence-based bundles, carefully calibrated to specific local contexts, offers a promising pathway to accelerating varietal adoption, turnover, and seed replacement.

- **Make significant investments in both formal and informal seed system infrastructure and regulatory reforms** to fully realize the potential of crop genetic innovation. Policy reforms should enhance seed quality assurance, improve intellectual property frameworks, streamline varietal registration and release processes, and encourage private sector investment.
- **Strengthen global consensus on the role of science—particularly precision genetics—in food systems.** This includes an urgent need for greater investment in rigorous impact assessments, using both predictive modeling and real-world evaluations to capture context-specific outcomes as well as broader impacts on economies.
- **Integrate systematic use of market intelligence to align crop improvement with climate change, urbanization, and shifting diets.** This will require an improved understanding of how crop genetic improvement programs use market intelligence, and what barriers they face in adopting more systematic and transdisciplinary processes for prioritization.

Crop improvement has long been a cornerstone of global efforts to enhance agricultural productivity, improve food security, and foster economic development. By conserving, sharing, and developing genetic materials that are used to develop high-yielding, stress-resistant, and more nutritious varieties, CGIAR genebanks, crop improvement programs, and seed system projects have contributed substantially to the efforts of national partners to deliver genetic gain—that is, genetic traits embodied in seeds and other types of planting material—to small-scale, resource-poor farmers. Together with national research programs, extension services, private seed companies, and women and men farmers' organizations, CGIAR has helped improve income, nutrition, and livelihood opportunities for both the rural and urban poor.

IFPRI researchers and the wider community of applied economists and policy analysts have consistently gravitated to studying crop improvement, although over time, the focus of policy research has evolved significantly. Early analyses by IFPRI and partners in the 1980s and 1990s provided evidence of the potential social and economic gains from public investment in plant breeding, supported by findings from field-based studies of varietal adoption

patterns, trends, and impacts. While governments in low- and middle-income countries (LMICs) continue to invest in genetic innovation and seed systems to support smallholder farmers, concerns have emerged about persistently low and heterogeneous rates of adoption among farmers in many agricultural systems. As a result, more recent research has focused on alleviating institutional and behavioral constraints to adoption and introducing innovative mechanisms to accelerate adoption and realize productivity and welfare outcomes.

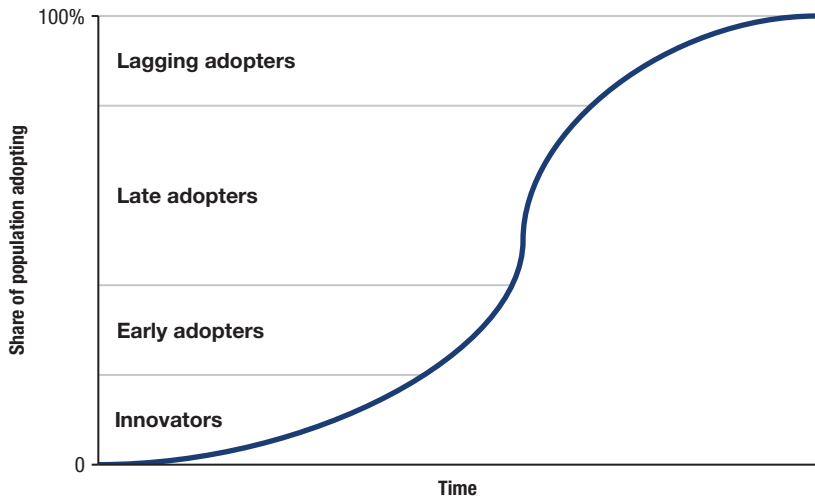
Policy research has also undergone a shift in focus from the original challenge of replacing landraces and local varieties with high-yielding improved varieties to an emphasis on (1) continuously replacing older improved varieties with more recently released varieties (*varietal turnover*), (2) encouraging farmers to cultivate high-quality seed irrespective of genetic change (*seed replacement*), and (3) moving from a singular focus on higher yields to targeting multiple traits, including abiotic stress tolerance, pest and disease resistance, improved use-efficiency for resources such as soil nutrients and water, higher micronutrient content, specific processing and preparation qualities, and other farmer-, consumer-, and market-facing characteristics. Combined, these shifts aim to make improved varieties more attractive to farmers, consumers, and other value chain actors, and also strengthen the contribution of crop varieties to addressing major food systems challenges such as climate change and dietary transitions.

In this chapter, we explore evidence on the contribution of crop genetic improvement to productivity, nutrition, environment, and poverty outcomes. We also discuss important areas for future research, such as documenting the empirical impacts and cost-effectiveness of innovations through which new varieties reach farmers; improving our understanding of how to accelerate varietal adoption, turnover, and quality seed use; and providing insights on the role of information, incentives, and policies in amplifying the impacts that crop genetic improvement may have on a range of development outcomes.

Evidence on crop improvement and farmer uptake

Identifying solution-oriented, evidence-based approaches to accelerate varietal adoption and turnover

Researchers have been interested in the economic and social dimensions of technological change in agriculture for decades. Seminal work in the late 1950s and early 1960s provided the iconic logistic growth functions, or “s-curves,” that are still used today to describe the process by which new technologies are adopted by

FIGURE 9.1 The classic adoption curve

Source: Adapted from Rogers (1962).

different types of farmers over time (Figure 9.1) (Griliches 1957; Rogers 1962). Given the expected impacts of improved varieties on productivity and poverty, a major emphasis for policy researchers has been to produce evidence on how to speed up the rate at which genetic gains reach farmers' fields.

Early research focused on the *adoption* of improved varieties, which is typically defined as the sustained replacement of landraces or local varieties by varieties that were improved by breeding programs (Spielman and Smale 2017). Adoption involves a significant change in the genetic composition of varieties being cultivated by farmers. Over a period of about 20 years starting in the mid-to-late 1960s, the Green Revolution experience with semi-dwarf rice and wheat varieties in South and Southeast Asia provided much of the evidence on the nature and impact of the adoption process (Evenson and Gollin 2003; Foster and Rosenzweig 1995; Lipton and Longhurst 1989). IFPRI researchers and colleagues shaped many of the early studies on adoption—not just of high-yielding rice and wheat varieties, but also of other country–crop combinations such as maize in Southern Africa (Smale et al. 1995) and rice and millet in West Africa (Adesina and Zinnah 1995; Smale et al. 2018).

Despite early successes in increasing productivity and reducing hunger and poverty (Fan et al. 2008; Hazell and Ramasamy 1991), evidence from

subsequent decades and regions tends to suggest low and variable adoption rates that are associated with a wide range of factors (Feder et al. 1985; Feder and Umali 1993). Particular emphasis was given to the slow rate of varietal *turnover*, that is, the replacement of first-generation varieties with more recently released varieties that sustain or enhance the original gains, such as pest and disease resistance (Brennan and Byerlee 1991; Heisey and Brennan 1991). Findings often pointed to adoption constraints such as the farmer's education level, landholding size, access to extension, or gender of the household head, and the need for more targeted efforts to reach the types of farm-households that are less likely to adopt new varieties.

Interest in accelerating adoption remains strong especially in Africa south of the Sahara, as concerns persist over slow or stagnant productivity growth in agriculture (Ray et al. 2012; Wollburg et al. 2024). But as many farmers in the Global South have become aware of improved varieties (for example, see Sheahan and Barrett 2017), policy emphasis is shifting slowly toward a combined approach: accelerating adoption where it is still lagging, and accelerating varietal turnover and seed replacement in most other places. Accelerating adoption will require a major shift in farmers' technology paradigm—the what, when, and how of their farming decisions, which are often shaped by the support provided by agricultural extension services, seed suppliers, starter kits, and fertilizer-seed-credit packages. Varietal turnover and seed replacement is often more continuous and incremental in nature, and more dependent on functional markets, institutions, and targeted policies.

Beyond their support to public plant breeding programs and extension services, governments often view seed subsidies as their primary policy instrument for promoting turnover and replacement. Subsidies address farmers' most obvious constraint—high sensitivity to seed prices (Mason and Ricker-Gilbert 2013; Mason and Smale 2013)—but often fail to address other important incentive issues and desirable outcomes, such as diversification in the crops that farmers produce (which contributes to soil health and dietary diversity in the home), unless intentionally designed to address these shortcomings (Spielman and Smale 2017). For example, in Malawi, introducing subsidies for legumes in addition to maize led to measurable improvements in diets (Matita et al. 2022).

Studies have also examined alternative explanations for low adoption, turnover, and replacement, looking, for example, at farmers' and consumers' preferred traits to inform product development priorities in breeding programs (Chowdhury et al. 2011; Oparinde et al. 2016), at how farmers obtain seed with these traits when markets are fragmented or absent (Lipper et al. 2010),

and at how specific regulations or program interventions could increase accessibility and affordability (Smale 2005; Tripp and Louwaars 1997).¹

Another branch of research builds on behavioral insights derived from exchanges between social psychology, economics, and public policy, and engages with seminal issues such as farmer heterogeneity (Suri 2011), learning processes (Foster and Rosenzweig 1995; Leathers and Smale 1991), risk and uncertainty (Rosenzweig and Binswanger 1993), and social institutions such as gender norms (Galiè et al. 2025). Studies on downside risk, learning dynamics, and imperfect markets for a wide range of crops and countries represent an important expansion of the evidence base and suggest ways to encourage adoption, turnover, and replacement by alleviating behavioral constraints (Gars and Ward 2019; Hanna et al. 2014).

One means of alleviating these constraints is by combining new varieties with other essential inputs and services. The rationale for bundling improved varieties with products such as advisories, finance, insurance, fertilizers, or market guarantees, is that farmers face multiple barriers to technology adoption, especially more marginalized farmers (Suri and Udry 2022) (see also Chapter 8). Marketing a new variety to risk-averse farmers, for example, may succeed only if it is accompanied by a small loan to address liquidity and credit constraints, a low-cost index insurance policy to address weather risk, digital advisories to provide easy access to technical and business insights, product quality assurance signals, or contracts to ensure postharvest market opportunities.² Similarly, providing information to women farmers or adjusting the manner in which the information is delivered to them may increase their capacity to make informed decision-making on, and their bargaining power over, which varieties to plant (Lecoutere et al. 2023; Kramer, Trachtman, and Zuze 2023).

The idea that improved varieties can be bundled with other products, services, and programs is not new. Packages of improved varieties, inorganic fertilizer, credit, extension services, and minimum support pricing were a hallmark of the Green Revolution. What is new, however, is the expansion of bundling options into entirely new realms of activity, as well as the commitment

1 Early research on these questions relied mainly on nonexperimental methods such as dichotomous choice models to establish correlations between adoption and its potential drivers; quasi-experimental methods requiring strong assumptions to (weakly) identify causal effects of innovations to increase adoption; or qualitative approaches that provide insufficient generalizability beyond small samples of farmers.

2 On credit, see Kramer et al. (2024); on insurance, see Boucher et al. (2024) and Ward et al. (2020); on digital advisories, see Fabregas et al. (2025, 2019); on product quality assurance signals, see Mieke, Swallow et al. (2023), Mieke, Van Campenhout et al. (2023), Bold et al. (2017), and Hsu and Wambugu (2022); and on contracts, see Arouna et al. (2021) and Michler and Wu (2020).

to generating rigorous evidence of what works and for whom (Barrett et al. 2020). While bundles may differ significantly by crop, country, market, or context, each one represents an opportunity for experimentation and learning, in which improved varieties contribute to the larger process of technical change and system transformation (see Chapter 8).

In fact, experiments that explore the impact of these bundles are providing actionable policy recommendations that address last-mile delivery problems for improved varieties. For example, bundling stress-tolerant varieties with index insurance products requires careful calibration of the index to the variety's performance under stress, such as moderate to severe drought during key stages of the plant's growth. The index should trigger payouts only once reaching a "tipping point" at which the stress-tolerance trait is overwhelmed, such as extreme drought that continues for several days beyond the plant's capacity to withstand drought (Ward et al. 2020; Lybbert and Carter 2014). Even then, farmers may not consider stress-tolerant varieties and insurance coverage to be complementary (Kramer, Waweru, and Malcarne 2023). Costing insurance requires not only an understanding of the probability that extreme events might occur, and the value of the potential losses, but also the discounts required to encourage smallholders to purchase coverage despite their lack of familiarity with index insurance (see also Chapter 10).

Creating an enabling environment to incentivize public and private innovation to accelerate varietal turnover

Experiments that have focused on addressing demand-side barriers to adoption tend to test solutions that increase demand for improved varieties made available through formal channels—primarily commercial seed markets—rather than through the nonmarket exchanges of seed on which many smallholder farmers rely. Thus, whereas innovations in bundled solutions to increase demand have advanced rapidly, broader seed systems innovations to strengthen both formal and informal channels are evolving more slowly. This slow pace has spurred an emphasis on upstream and midstream value chain development (Reardon and Timmer 2012), as well as lessons learned from private industry (Donovan et al. 2021; ter Steeg and Louwaars 2024), to design innovative approaches that address supply-side constraints to adoption, turnover, and replacement.

Seed systems innovations include a sequence of supply-side regulatory reforms and demand-side investments designed to attract private investment into the delivery of improved varieties and quality seeds to smallholder farmers, while they also draw attention to the economic trade-offs, unintended

consequences, and operational challenges of such reforms and investments. Producing marketable seeds requires land, labor, irrigation, regulation, capital, expertise, and business and marketing experience to forecast and generate demand, all of which can be scarce in LMICs, thus introducing supply-side constraints in their seed industries. Lifting these constraints is important for firms and market regulators in order to ultimately make new varieties available to farmers and other value chain actors. Unfortunately, compared to investments in crop improvement, investments in seed production and other production-related aspects of the seed system have been relatively small.

Although many private companies in Asia have achieved notable successes in the seed industry, Africa's seed sector remains at a relatively nascent stage. Initiatives such as the Program for Africa's Seed Systems, led by AGRA (formerly the Alliance for a Green Revolution in Africa), and the Integrated Seed Sector Development project, led by Wageningen University & Research, have contributed to mobilizing attention and resources around the policy dimensions of seed sector development, especially where formal (commercial) and informal (farmer-based) seed systems intersect (Bagamba et al. 2023; Munyi and De Jonge 2015; Wellard et al. 2019). Similar efforts such as the Enabling the Business of Agriculture indicators, the African Seed Access Index, and the Access to Seeds Index, combined with CGIAR programs and projects, have also drawn attention to the need for a stronger enabling environment. Emphasis has been placed on early generation seed production and distribution, varietal registration and release procedures, seed quality assurance systems, intellectual property rights, seed subsidies, and international seed trade (Kuhlmann 2021; Spielman and Smale 2017).

Demonstrating how public investment in crop improvement can generate desirable development outcomes

IFPRI and its partners continue to conduct research that quantifies the social returns to improved variety development and delivery, justifies the necessary investment of scarce public resources, and unpacks the political economy factors that shape the policy discourse around crop improvement.

Research spanning several decades has helped to demonstrate how public spending on agricultural R&D—usually involving plant breeding programs as the primary funding vehicle—contributes to agricultural productivity growth (Alston and Pardey 2021; Alston et al. 1995, 2022; Griliches 1964; Hayami and Ruttan 1971). More recent evidence has helped to solidify the connection between crop improvement and productivity growth (Evenson and Gollin 2003), while other work has extended this analysis to link R&D and poverty

outcomes (Fan et al. 2000; Fan and Hazell 2001). A recent *ex ante* impact assessment suggests that faster productivity growth due to crop improvement could increase economywide income by 2 to 15 times the current level of public R&D spending on food crops in LMICs, with the potential to reduce the population at risk of hunger by up to 11 million people (Wiebe et al. 2021).

This entire body of literature draws on a rich combination of analytical techniques and data sources, ranging from econometric analysis using national statistics on crop production, yields, and area (Fan et al. 2000; Fan and Hazell 2001), relatively straightforward economic surplus models (Fuglie and Echeverria 2024), structural models estimating the impacts of the Green Revolution (Gollin et al. 2021), and sophisticated global computational models (Evenson and Rosegrant 2003; Rosegrant et al. 2023). Models developed or improved upon by IFPRI, such as DREAM, RIAPA, IMPACT, and MIRAGRODEP, have played a critical role in the latter type of research, as has the Institute's statistical and econometric modeling (see also Chapter 4).

While many of these studies have withstood the test of time and remain seminal to our understanding of crop improvement's importance, the nature of the evidence is rapidly evolving, including the methods being applied to demonstrate impacts (Box 9.1). In particular, there is a move to use more rigorous experimental and quasi-experimental methods to establish causal relationships with greater credibility, precision, and context-specificity (Stevenson et al. 2023). For example, randomized controlled trials (RCTs) have become a cornerstone of evidence-based policy evaluation, including the evaluation of impacts from using improved varieties under farmers' conditions (for example, Emerick et al. 2016; Boucher et al. 2024).

Using RCTs to evaluate the impacts of crop improvement, as has been done by IFPRI researchers for a variety of crops in Africa and Asia, has helped create the evidence needed to advance these traits into widespread use by farmers.³ IFPRI-led studies also shed light on which incentives and institutions lead to changes in farmers' expectations, preferences, and behaviors, and ultimately shape their adoption, turnover, and replacement decisions in cost-effective and inclusive ways. Importantly, whether they rely on relatively simple economic surplus models or complex global trade ones, these RCT-based methods offer greater analytical resolution and nuance at the country, crop, and trait levels than modeling-based approaches, despite well-reasoned criticisms of the approach (Barrett and Carter 2020, 2010; Rosenzweig and Udry 2020).

3 Examples of RCT-based studies include Abate et al. (2018, 2023); Ahmed et al. (2021); Bernard et al. (2023); De Brauw et al. (2018, 2019); and Van Campenhout et al. (2021).

BOX 9.1 Methods for assessing the impacts of crop improvement

Research on crop improvement must consider whether the social returns justify investing scarce public resources in plant breeding. Below, we examine the variety of approaches used to address this question.

EX ANTE MODELING-BASED IMPACT ASSESSMENTS. Continuous ex ante assessments of crop improvement programs and other development interventions are essential to justifying and prioritizing scarce public resources. These assessments utilize economic models such as DREAM, RIAPA, IMPACT, MIRAGRODOP, and GLOBE, as well as biophysical models and data to enhance and calibrate these models. They conceptualize outputs from investments in breeding as “innovations” that increase productivity growth, and then quantify the returns to agricultural R&D and the contribution of crop improvement by comparing scenarios with and without adoption of improved varieties (that is, with higher versus lower rates of productivity growth). This method is often used to inform investments in agricultural R&D. An advantage is that the use of macroeconomic models facilitates comparison across regions, crops, and outcome indicators to identify where the greatest gains can be achieved, depending on the diverse objectives of donors and other decision-makers. However, the approach requires making strong assumptions about the effects of improved varieties on yield growth and about the relationship between yield growth and poverty reduction, food security, and nutrition, neither of which are always founded in empirical observations.

AGRONOMIC PERFORMANCE TRIALS. Field trials play a pivotal role in evaluating the real-world performance of new crop varieties. Conducted under controlled conditions in diverse agro-ecological settings, these trials measure agronomic traits such as yield, resistance to pests and diseases, and adaptation to local conditions. Data from these trials inform breeders, farmers, and policymakers about the practical implications of adopting new varieties and their comparative advantages over existing ones. However, performance under controlled conditions does not always translate into similar performance under farmers’ practices. Under uncontrolled conditions, the decision to adopt a new variety could introduce behavioral responses that cannot be captured through this type of method.

ADOPTION STUDIES. Studies documenting the adoption of new crop varieties provide empirical evidence on the extent to which varieties are adopted, perceptions of those varieties, and reasons for adoption or non-adoption. These studies often aim to document changes in agricultural practices and productivity associated with adopting new varieties by comparing adopters and nonadopters. Given that the decision to adopt a new variety is likely

correlated with unobservable farmer characteristics that also influence agricultural practices and productivity, findings from adoption studies should not be interpreted as causal evidence. Nonetheless, insights gained from these studies are critical for understanding the rate of adoption of improved varieties, farmers' perceptions of these varieties, and potential barriers to adoption, all of which can be used to design effective extension and outreach programs.

EMPIRICAL (QUASI-)EXPERIMENTAL EVALUATIONS. None of the methods described above show that investments in crop improvement have an impact on the ground. Rigorous evaluations employ robust methodologies such as randomized controlled trials (RCTs) or quasi-experimental designs to assess the causal impact of offering new crop varieties. By randomly assigning treatments that introduce exogenous variation in the probability of accessing and/or adopting the new variety, these evaluations measure the direct effects of adopting new varieties on agricultural productivity, income generation, food security and nutrition, gender equity, the ability to protect consumption or investments from climate shocks, and other indicators of impact. The use of RCTs in policy research is an extension of methods regularly employed by breeders and agronomists, wherein plants, rather than people, are compared across treatment and control groups in highly controlled environments. The main difference is that policy researchers observe people rather than plants, looking at the choices that individual farmers make and the benefits that can be achieved, given their own preferences, expectations, and constraints. Such evaluations provide credible evidence for policymakers and development practitioners to prioritize investments in crop improvement programs. Evidence from such evaluations could also be used to verify whether the impacts predicted *ex ante* by computational models did indeed occur and to refine model calibration with empirically observed adoption and impact estimates.

Looking to the future

Strengthening opportunities for impact through crop improvement and seed systems

Looking to the future, the cumulative evidence strongly suggests that a better understanding of the impact pathways leading from genetic improvement to broader developmental outcomes can potentially improve the efficiency and effectiveness of future policy and investment choices. This is particularly relevant when such choices aim to address large and complex agricultural

transformation challenges beyond productivity growth or poverty reduction, such as better diets and nutrition, climate adaptation and mitigation, gender equity, social inclusion, and addressing environmental degradation and biodiversity loss.

This means moving beyond yield improvement as the sole indicator of breeding progress. Since it is well recognized that a new variety often will not succeed with farmers if its yield is not at least equal to the incumbent variety, the question becomes what other traits should be targeted in product profiles. Potential targets include abiotic stress-tolerance traits for drought, flood, heat, cold, and other adverse weather events induced by climate change; abiotic stress-resistance traits for existing or new pests and diseases that flourish in changing climatic conditions; and nutrition traits conferred by biofortification, that is, breeding for traits that enhance the micronutrient content of food staples (Bouis et al. 2024). National research centers and breeding programs have invested significantly in all of these areas with their CGIAR partners, with standout examples including CIMMYT's Drought Tolerant Maize for Africa, IRRI's Stress Tolerant Rice for Africa and South Asia, and HarvestPlus's work across CGIAR on biofortification, among many others.

Opportunities exist to target other impacts of crop improvement, such as addressing gender equality by targeting production or processing traits that reduce drudgery for women, or by focusing on crops traditionally grown and marketed by women. Some breeding programs have documented or emphasized women's and men's preferred varietal traits and incorporated gender into their participatory breeding and variety selection processes (Ashby and Polar 2019; Weltzien et al. 2019). Programs with explicit gender objectives have made considerable progress in advancing gender equity by supporting women's empowerment, addressing discriminatory gender norms, or creating social and economic opportunities for women (Galiè et al. 2025). However, less emphasis has been placed on identifying which supply- and demand-side interventions can equitably improve varietal adoption, turnover, and replacement (Kramer and Trachtman 2024). There is still a strong need for testing new product concepts and complementary solutions among diverse groups of individuals.

Breeding better crops and delivering them to farmers will never be a simple "silver bullet" solution to achieve productivity growth, poverty reduction, improved nutrition, climate resilience, gender and social equity, or environmental sustainability. Given the complexity of these challenges, no set of traits in a given variety of a single crop can address all of them simultaneously. Even

with a proven “blockbuster” crop variety, it is impossible to simultaneously address the diverse needs of heterogeneous farmers who operate under different agroecological and socioeconomic conditions. Therefore, a more nuanced approach is needed that bundles together combinations of technological, technical, and social innovations to address multiple outcomes and achieve stronger and more equitable impacts (Barrett et al. 2020, 2022). Behavioral, social, and economic intelligence is key to identifying opportunities and constraints through which these sociotechnical bundles can help improve adoption and strengthen impacts.

Future priorities for policy and policy research

Looking forward, ensuring that improved varieties and quality seed have a sizable impact on development outcomes in the run-up to 2050 will require several actions.

Build a stronger global consensus around the role of science and technology in our food systems. From the very basic tenets of Mendelian genetics to the role of vaccines in society, science is under siege in many communities. For decades, IFPRI and partners have explored the social and economic impacts of improved genetics in agriculture, helping to demonstrate that science is critical to ending global hunger, malnutrition, and poverty. As the pace of scientific achievement increases, precision genetics will likely play a role in agriculture, as it already does in the healthcare and pharmaceutical sectors, among many others. IFPRI-led studies on genetically modified crops, gene editing, marker-assisted selection, and other applications of genetics and molecular biology to agriculture in the Global South have contributed to ongoing debates around scientific evidence,⁴ complementing other independent and influential sources on the role of precision genetics in our global food system (Qaim 2016). Choices on which technologies to move forward should and will be science-based even when public perception suggests otherwise (Paarlberg 2023).

- Evidence is essential to mobilizing science to both safeguard and improve human and environmental health through crop improvement programs and seed sector development.

⁴ This work includes Falck-Zepeda and Zambrano (2011), Omamo and Von Grebmer (2005), Pixley et al. (2022, 2019), and Smale et al. (2009).

Use market intelligence systematically in crop improvement programs and seed sector development. This is especially important in light of major global challenges related to climate change, dietary transitions, and rapidly evolving food systems. Market intelligence brings together strategic information on future crops, market segments, trait preferences, and client needs to inform decisions and prioritize investments in breeding pipelines and seed systems. It can offer analytical insights that shape the entire product design process from the selection of desired traits to placement in an appropriate market segment. Such information can reorient investments in crop improvement to address climate change and associated shifts in what types of varieties can be grown where, as well as to accommodate changes in dietary preferences in a more urbanized and marketized world, where most people purchase their food rather than grow it themselves.

- IFPRI's economic policy models and its data assets from large-scale household surveys can help inform this prioritization process by providing ex ante projections of potential returns on investment in a given pipeline, or by providing more granular subnational estimates of indicators for various impact areas, such as poverty, food security, dietary diversity, malnutrition, women's empowerment, and resilience to climate change.

Employ IFPRI's behavioral research to provide insights on how to encourage the use of market intelligence. Systematic processes for gathering and using market data remain rare, with evidence showing that less than 45 percent of surveyed breeding professionals use structured methods (Rice et al. 2024). Power dynamics and attitudes further limit meaningful contributions from social scientists (Cullen et al. 2023). Without high-quality market data or cross-disciplinary collaboration, decision-makers risk relying on imprecise or biased information, hindering effective prioritization of breeding investments, and limiting impactful investments in crop improvement. An online experiment suggests that breeding experts, including natural and social scientists involved in plant breeding, may over-extrapolate from low-quality data and may be biased to prefer cheaper, lower-quality information from disciplines that are more familiar to them (Trachtman et al. 2024). This research highlights the need to strengthen awareness of data quality in market research for impactful R&D prioritization and to quantify the gains from increasing such awareness, expanding data availability to prioritize investments, and investing in the systematic use of such information.

Increase investment in assessing the impact of improved varieties and quality seed. This should include complementing ex ante modeling with rigorous empirical measurement of impacts and cost-effectiveness using randomized evaluations that can capture context-specific granularity and shed light on institutional and behavioral mechanisms, such as adoption rates, crowding-out or crowding-in of other inputs, and impacts for diverse groups of farmers, who are otherwise elusive in a modeling framework due to unobservable preferences, risks, expectations, or other factors that are difficult to discern.

- Recent CGIAR efforts to strengthen impact assessment of crop improvement through coordinated trials across a wide range of settings (Kilonzi et al. 2025) will be instrumental, as are ongoing studies to evaluate the impact of various socio-technical bundles.

Link ex ante modeling with ex post evaluations to refine policy guidance for governments and their development partners. For instance, models used for ex ante impact assessment could be updated with robust and externally valid empirical estimates of adoption of new improved varieties under realistic seed system scenarios, as well as their potential effects on productivity. Conversely, general equilibrium effects should be considered more extensively, especially in labor and other factor markets, beyond the immediate first-order outcomes of a given intervention, which are captured through randomized evaluations.

- Using findings from ex post evaluations to estimate general equilibrium effects is an important area of further research (Rosenzweig and Udry 2020; Taylor and Filipowski 2014).

Improve the policy, regulatory, and investment landscape. Significant changes are needed in the landscape that shapes the performance of crop improvement programs and seed sector development efforts. Of particular importance are the international agreements and national policies governing the exchange of genetic resources for crop improvement purposes that affect both innovation and entrepreneurship. This includes designing and implementing intellectual property rights regimes that address both breeders' and farmers' rights to plant genetic resources and the gains from innovation, and national varietal registration and release processes and mutual recognition of released varieties through regional regulatory harmonization to increase access to genetic gain across borders (Bishaw et al. 2025), as well as the role of genebanks in conserving genetic resources for future generations (Halewood et al. 2012; Koo et al. 2003; Mekonnen and Spielman 2021). At a more local level, this includes

addressing the production and equitable distribution of early generation seed to facilitate commercial firms, farmer-based enterprises, and seed sector development, and the design of credible seed quality assurance systems.

- IFPRI's role in this area is to inform efforts to improve policy, regulatory, and investment landscapes, and to evaluate costs and benefits of doing so.

Conclusion

Research by IFPRI and the wider policy research community highlights the continued importance of plant breeding, crop improvement, and seed sector development. Improved varieties, varietal turnover, and seed replacement will remain key drivers of technical change among smallholder farmers, with benefits that include lower food prices for workers, income and livelihood opportunities for rural farm and nonfarm households, and low-cost inputs for firms in the service and industrial sectors. A rich body of work demonstrates the value of investing in genetic innovation and delivering these innovations to farmers' fields. However, the technology adoption paradox continues to frustrate many observers and decision-makers: with so much invested in agricultural R&D, why are the rates of improved variety adoption, variety turnover, and seed replacement so low and variable across crops and countries in the Global South? The answer can be found in the specificities of crops, people, and places, though that should not prevent investment in generating evidence-based recommendations to affect policy. Key areas for future consideration include building a stronger global consensus around the role of science and technology in our food systems, applying data-driven market intelligence to prioritize breeding, and advancing dramatic policy, regulatory, and investment reforms to reshape the performance of crop improvement programs and seed sector development efforts.

References

- Abate, G.T., T. Bernard, A. de Brauw, and N. Minot. 2018. "The Impact of the Use of New Technologies on Farmers' Wheat Yield in Ethiopia: Evidence from a Randomized Control Trial." *Agricultural Economics* 49 (4): 409–421.
- Abate, G.T., T. Bernard, S. Makhija, and D.J. Spielman. 2023. "Accelerating Technical Change Through ICT: Evidence from a Video-Mediated Extension Experiment in Ethiopia." *World Development* 161: 106089.
- Adesina, A.A., and M.M. Zinnah. 1993. "Technology Characteristics, Farmers' Perceptions and Adoption Decisions: A Tobit Model Application in Sierra Leone." *Agricultural Economics* 9 (4): 297–311.
- Ahmed, A.U., J. Hoddinott, N. Abedin, and N. Hossain. 2021. "The Impacts of GM Foods: Results from a Randomized Controlled Trial of Bt Eggplant in Bangladesh." *American Journal of Agricultural Economics* 103 (4): 1186–1206.
- Alston, J.M., G.W. Norton, and P.G. Pardey. 1995. *Science Under Scarcity*. Ithaca, NY: Cornell University Press.
- Alston, J.M., and P.G. Pardey. 2021. "The Economics of Agricultural Innovation." *Handbook of Agricultural Economics* 5: 3895–3980.
- Alston, J.M., P.G. Pardey, and X. Rao. 2022. "Payoffs to a Half Century of CGIAR Research." *American Journal of Agricultural Economics* 104 (2): 502–529.
- Arouna, A., J.D. Michler, and J.C. Lokossou. 2021. "Contract Farming and Rural Transformation: Evidence from a Field Experiment in Benin." *Journal of Development Economics* 151: 102626.
- Ashby, J.A., and V. Polar. 2019. "The Implications of Gender Relations for Modern Approaches to Crop Improvement and Plant Breeding." In *Gender, Agriculture and Agrarian Transformations*, ed. C.E. Sachs, 11–34. London: Routledge.
- Bagamba, F., P.R. Ntakyo, G. Otim, D.J. Spielman, and B. Van Campenhout. 2023. "Policy and Performance in Uganda's Seed Sector: Opportunities and Challenges." *Development Policy Review* 41 (3): 12665.
- Barrett, C.B., T. Benton, K.A. Cooper et al. 2020. "Bundling Innovations to Transform Agri-Food Systems." *Nature Sustainability* 3 (12): 974–976.
- Barrett, C.B., T.G. Benton, J. Fanzo, et al. 2022. *Socio-Technical Innovation Bundles for Agri-Food Systems Transformation*. Cham, Switzerland: Springer Nature.
- Barrett, C.B., and M.R. Carter. 2010. "The Power and Pitfalls of Experiments in Development Economics: Some Non-Random Reflections." *Applied Economic Perspectives and Policy* 32 (4): 515–548.

- Barrett, C.B., and M.R. Carter. 2020. "Finding Our Balance? Revisiting the Randomization Revolution in Development Economics Ten Years Further On." *World Development* 127: 104789.
- Bernard, T., S. Lambert, K. Macours, and M. Vinez. 2023. "Impact of Small Farmers' Access to Improved Seeds and Deforestation in DR Congo." *Nature Communications* 14 (1): 1603.
- Bishaw, Z., Y. A.Yigezu, and G. Berhane. 2025. *Where Do We Stand After Ten Years of Harmonized Seed Trade Regulations in COMESA? Case Studies from Egypt and Sudan*. Policy Brief. CGIAR Initiative on Fragility to Resilience in Central and West Asia and North Africa. Montpellier: CGIAR.
- Bold, T., K.C. Kaizzi, J. Svensson, and D. Yanagizawa-Drott. 2017. "Lemon Technologies and Adoption: Measurement, Theory and Evidence from Agricultural Markets in Uganda." *The Quarterly Journal of Economics* 132 (3): 1055–1100.
- Bold, T., S. Ghisolfi, F. Nsonzi, and J. Svensson. 2022. "Market Access and Quality Upgrading: Evidence from Four Field Experiments." *American Economic Review* 112 (8): 2518–2552.
- Boucher, S.R., M.R. Carter, J.E. Flatnes, T.J. Lybbert, J.G. Malacarne, P.P. Mareyna, and L.A. Paul. 2024. "Bundling Genetic and Financial Technologies for More Resilient and Productive Small-Scale Farmers in Africa." *The Economic Journal* 134 (662): 2321–2350.
- Bouis, H., J. Foley, K. Lividini, et al. 2024. "Biofortification: Future Challenges for a Newly Emerging Technology to Improve Nutrition Security Sustainably." *Current Developments in Nutrition* 8 (12): 104478.
- Brennan, J.P., and D. Byerlee. 1991. "The Rate of Crop Varietal Replacement on Farms: Measures and Empirical Results for Wheat." *Plant Varieties and Seeds* 4: 99–106.
- Chowdhury, S., J.V. Meenakshi, K.I. Tomlins, and C. Owor. 2011. "Are Consumers in Developing Countries Willing to Pay More for Micronutrient-Dense Biofortified Foods? Evidence from a Field Experiment in Uganda." *American Journal of Agricultural Economics* 93 (1): 83–97.
- Cullen, B., A. Snyder, D. Rubin, and H.A. Tufan. 2023. "'They Think We Are Delaying Their Outputs.' The Challenges of Interdisciplinary Research: Understanding Power Dynamics Between Social and Biophysical Scientists in International Crop Breeding Teams." *Frontiers in Sustainable Food Systems* 7: 1250709.
- De Brauw, A., P. Eozenou, D.O. Gilligan, C. Hotz, N. Kumar, and J.V. Meenakshi. 2018. "Biofortification, Crop Adoption and Health Information: Impact Pathways in Mozambique and Uganda." *American Journal of Agricultural Economics* 100 (3): 906–930.
- De Brauw, A., M. Moursi, and A.B. Munhaua. 2019. "Vitamin A Intakes Remain Higher Among Intervention Participants 3 Years After a Biofortification Intervention in Mozambique." *British Journal of Nutrition* 122 (1): 1175–1181.

- Donovan, J., P. Rutsaert, D.J. Spielman, K.M. Shikuku, and M. Demont. 2021. "Seed Value Chain Development in the Global South: Key Issues and New Directions for Public Breeding Programs." *Outlook on Agriculture* 50 (4): 366–377.
- Emerick, K., A. De Janvry, E. Sadoulet, and M.H. Dar. 2016. "Technological Innovations, Downside Risk, and the Modernization of Agriculture." *American Economic Review* 106 (6): 1537–1561.
- Evenson, R.E., and D. Gollin, eds. 2003. *Crop Variety Improvement and its Effect on Productivity: The Impact of International Agricultural Research*. Wallingford, UK: CAB International.
- Evenson, R.E., and M. Rosegrant. 2003. "The Economic Consequences of Crop Genetic Improvement Programmes." In *Crop Variety Improvement and Its Effect on Productivity: The Impact of International Agricultural Research*, eds. R. E. Evenson, D. Gollin, 473–497. Wallingford, UK: CAB International.
- Fabregas, R., M. Kremer, M. Lowes, R. On, and G. Zane. 2025. "Digital Information Provision and Behavior Change: Lessons from Six Experiments in East Africa." *American Economic Journal: Applied Economics* 17 (1): 527–566.
- Fabregas, R., M. Kremer, and F. Schilbach. 2019. "Realizing the Potential of Digital Development: The Case of Agricultural Advice." *Science* 366 (6471): 3038.
- Falck-Zepeda, J.B., and P. Zambrano. 2011. "Socio-Economic Considerations in Biosafety and Biotechnology Decision Making: The Cartagena Protocol and National Biosafety Frameworks." *Review of Policy Research* 28 (2): 171–195.
- Fan, S., A. Gulati, and S. Thorat. 2008. "Investment, Subsidies, and Pro-Poor Growth in Rural India." *Agricultural Economics* 39 (2):163–170.
- Fan, S., and P.B.R. Hazell. 2001. "Returns to Public Investments in the Less-Favored Areas of India and China." *American Journal of Agricultural Economics* 83 (5): 1217–1222.
- Fan, S., P.B.R. Hazell, and S. Thorat. 2000. "Government Spending, Growth and Poverty in Rural India." *American Journal of Agricultural Economics* 82 (4): 1038–1051.
- Feder, G., and D.L. Umali. 1993. "The Adoption of Agricultural Innovations: A Review." *Technological Forecasting and Social Change* 43 (3–4): 215–239.
- Feder, G., R.E. Just, and D. Zilberman. 1985. Adoption of Agricultural Innovations in Developing Countries: A Survey," *Economic Development and Cultural Change* 33 (2): 255–298.
- Foster, A.D., and M.R. Rosenzweig. 1995. "Learning by Doing and Learning from Others: Human Capital and Technical Change in Agriculture." *Journal of Political Economy* 103 (6): 1176–1209.
- Fuglie, K.O., and R.G. Echeverria. 2024. "The Economic Impact of CGIAR-Related Crop Technologies on Agricultural Productivity in Developing Countries, 1961–2020." *World Development* 176 (2024): 106523.

- Galiè, A., B. Kramer, D.J. Spielman, N. Kawarazuka, A.M. Rietveld, and S. Aju. 2025. "Inclusive and Gender-Transformative Seed Systems: Concepts and Applications." *Agricultural Systems* 226: 104320.
- Gars, J., and P.S. Ward. 2019. "Can Differences in Individual Learning Explain Patterns of Technology Adoption? Evidence on Heterogeneous Learning Patterns and Hybrid Rice Adoption in Bihar, India." *World Development* 115 : 178–189.
- Gollin, D., W. Hansen, and A.M. Wingender. 2021. "Two Blades of Grass: The Impact of the Green Revolution," *Journal of Political Economy* 129 (8): 2344–2384.
- Griliches, Z. 1957. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25 (4): 501–522.
- Griliches, Z. 1964. "Research Expenditures, Education and the Aggregate Agricultural Production Function." *American Economic Review* 54 (6): 961–974.
- Halewood, M., I.L. Noriega, and S. Louafi. 2012. *Crop Genetic Resources as a Global Commons: Challenges in International Law and Governance*. Routledge.
- Hanna, R., S. Mullainathan, and J. Schwartzstein. 2014. "Learning through Noticing: Theory and Evidence from a Field Experiment." *The Quarterly Journal of Economics* 129 (3): 1311–1353.
- Hayami, Y., and V.W. Ruttan. 1971. *Agricultural Development: An International Perspective*. Baltimore: Johns Hopkins University Press.
- Hazell, P.B.R, and C. Ramasamy, eds. 1991. *The Green Revolution Reconsidered: The Impact of High-Yielding Rice Varieties in South India*. Baltimore: Johns Hopkins University Press for IFPRI.
- Heisey, P.W., and J. Brennan. 1991. "An Analytical Model of Farmers' Demand for Replacement Seed." *American Journal of Agricultural Economics* 73 (4): 1044–1052.
- Hsu, E., and A. Wambugu. 2022. "Can Informed Buyers Improve Goods Quality? Experimental Evidence from Crop Seeds." G²LM|LIC Working Paper 74, Gender, Growth, and Labour Markets in Low Income Countries Programme, IZA Institute of Labor Economics, Bonn, Germany.
- Kilonzi, E., B. Kramer, and C. Trachtman. 2025. "Workshop: Assessing On-the-Ground Impacts of Genetic Innovation in Agriculture." *IFPRI Blog*, January 15.
- Koo, B., P.G. Pardey, and B.D. Wright. 2003. "The Economic Costs of Conserving Genetic Resources at the CGIAR Centers." *Agricultural Economics* 29 (3): 287–297.
- Kramer, B., S. Pattnaik, P.S. Ward, and Y. Xu. 2024. *Impacts of an Innovative Credit+ Insurance Bundle for Marginalized Farmers: Evidence from a Cluster Randomized Trial in Odisha, India*. Washington, DC: IFPRI.
- Kramer, B., and C. Trachtman. 2024. "Gender Dynamics in Seed Systems: An Integrative Review of Seed Promotion Interventions in Africa." *Food Security* 16 (1): 19–45.

- Kramer, B., C. Trachtman, and L. Zuze. 2023. "Information as a Source of Empowerment: The Role of Climate Information Services," AICCRA Working Paper 17, Accelerating Impacts of CGIAR Climate Research for Africa, CGIAR, Montpellier, France.
- Kramer, B., C. Waweru, and J.G. Malacarne. 2023. "Summing the Parts: How Does 'Bundling' Affect Willingness-to-Pay for Seeds and Insurance in a Sample of Kenyan Farmers?" Conference Paper, IFPRI, Washington, DC.
- Kuhlmann, K. 2021. "Mapping Inclusive Law and Regulation: A Comparative Agenda for Trade and development." *African Journal of International Economic Law* 2: 48–87.
- Leathers, H.D., and M. Smale. 1991. "A Bayesian Approach to Explaining Sequential Adoption of Components of a Technological Package." *American Journal of Agricultural Economics* 73 (3): 734–742.
- Lecoutere, E., D.J. Spielman, and B. Van Campenhout. 2023. "Empowering Women Through Targeting Information or Role Models: Evidence from an Experiment in Agricultural Extension in Uganda." *World Development* 167 (2023): 106240.
- Lipper, L., C.L. Anderson, and T.J. Dalton, eds. 2010. *Seed Trade in Rural Markets Implications for Crop Diversity and Agricultural Development*. London: FAO and Earthscan.
- Lipton, M., and R. Longhurst. 1989. *New Seeds and Poor People*. London: Routledge.
- Lybbert, T.J., and M.R. Carter. 2014. "Bundling Drought Tolerance and Index Insurance to Reduce Rural Household Vulnerability." In *Sustainable Economic Development: Resources, Environment, and Institutions*, eds. A. Balisacan, U. Chakrovarty, and M. Ravago, 401–414. Oxford: Academic Press.
- Mason, N.M., and J. Ricker-Gilbert. 2013. "Disrupting Demand for Commercial Seed: Input Subsidies in Malawi and Zambia." *World Development* 45: 75–91.
- Mason, N.M., and M. Smale. 2013. "Impacts of Subsidized Hybrid Seed on Indicators of Economic Well-Being Among Smallholder Maize Growers in Zambia." *Agricultural Economics* 44 (6): 659–670.
- Matita, M., L. Chiwaula, E.W. Chirwa, J. Mazalale, and H. Walls. "Subsidizing Improved Legume Seeds for Increased Household Dietary Diversity: Evidence from Malawi's Farm Input Subsidy Programme with Implications for Addressing Malnutrition in All Its Forms." *Food Policy* 113 (2022): 102309.
- Mekonnen, D.K., and D.J. Spielman. 2021. "Changing Patterns in Genebank Acquisitions of Crop Genetic Materials: An Analysis of Global Policy Drivers and Potential Consequences." *Food Policy* 105: 102161.
- Michler, J.D., and S.Y. Wu., 2020. "Relational Contracts in Agriculture: Theory and Evidence." *Annual Review of Resource Economics* 12 (1): 111–127.

- Miche, C., R. Sparrow, D.J. Spielman, and B. Van Campenhout. 2023. “The (Perceived) Quality of Agricultural Technology and Its Adoption: Experimental Evidence from Uganda,” IFPRI Discussion Paper 02918, IFPRI, Washington, DC.
- Miche, C., B. Van Campenhout, L. Nabwire, R. Sparrow, and D.J. Spielman. 2023. “Miracle Seeds: Biased Expectations, Complementary Input Use, and the Dynamics of Smallholder Technology Adoption,” IFPRI Discussion Paper 02183, IFPRI, Washington, DC.
- Munyi, P., and B. De Jonge. 2015. “Seed Systems Support in Kenya: Consideration for an Integrated Seed Sector Development Approach.” *Journal of Sustainable Development* 8 (2): 161–173.
- Omamo, S.W., and K. von Grebmer, eds. 2005. *Biotechnology, Agriculture, and Food Security in Southern Africa*. Washington, DC: IFPRI.
- Oparinde, A., A. Banerji, E. Birol, and P. Ilona. 2016. “Information and Consumer Willingness to Pay for Biofortified Yellow Cassava: Evidence from Experimental Auctions in Nigeria.” *Agricultural Economics* 47 (2): 215–233.
- Pixley, K.V., J.B. Falck-Zepeda, K.E. Giller, et al. 2019. “Genome Editing, Gene Drives, and Synthetic Biology: Will They Contribute to Disease-Resistant Crops, and Who Will Benefit?” *Annual Review of Phytopathology* 57 (1): 165–188.
- Pixley, K.V., J.B. Falck-Zepeda, R.L. Paarlberg, et al. 2022. “Genome-Edited Crops for Improved Food Security of Smallholder Farmers.” *Nature Genetics* 54 (4): 364–367.
- Qaim, M. 2016. *Genetically Modified Crops and Agricultural Development*. London: Palgrave Macmillan.
- Ray, D.K., N. Ramankutty, N.D. Mueller, P.C. West, and J.A. Foley. 2012. “Recent Patterns of Crop Yield Growth and Stagnation,” *Nature Communications* 3 (1): 1293.
- Reardon, T., and C.P. Timmer. 2012. “The Economics of the Food System Revolution.” *Annual Review of Resource Economics* 4 (1): 225–264.
- Rice, B., B. Kramer, and C. Trachtman. 2024. *Barriers to Using Market Intelligence in Plant Breeding: Evidence from a Survey of Breeding Professionals*. Market Intelligence Brief Series no. 21. Montpellier: CGIAR.
- Rogers, E.M. 1962. *Diffusion of Innovations*. New York: Free Press.
- Rosegrant, M.W., B. Wong, T.B. Sulser, N. Dubosse, and T.J. Lybbert. 2023. “Benefit–Cost Analysis of Increased Funding for Agricultural Research and Development in the Global South.” *Journal of Benefit-Cost Analysis* 14 (S1): 181–205.
- Rosenzweig, M.R., and H.P. Binswanger. 1993. “Wealth, Weather Risk and the Composition and Profitability of Agricultural Investments.” *Economic Journal* 103 (416): 56–78.
- Rosenzweig, M.R., and C. Udry. 2020. “External Validity in a Stochastic World: Evidence from Low-Income Countries.” *Review of Economic Studies* 87 (1): 343–381.

- Sheahan, M., and C.B. Barrett. 2017. "Ten Striking Facts about Agricultural Input Use in Sub-Saharan Africa." *Food Policy* 67: 12–25.
- Smale, M., ed. 2005. *Valuing Crop Biodiversity: On-Farm Genetic Resources and Economic Change*. Wallingford, UK: CABI Publishing.
- Smale, M., A. Assima, A. Kergna, V. Thériault, and E. Weltzien. 2018. "Farm Family Effects of Adopting Improved and Hybrid Sorghum Seed in the Sudan Savanna of West Africa." *Food Policy* 74: 162–171.
- Smale, M., P.W. Heisey, and H.D. Leathers. 1995. "Maize of the Ancestors and Modern Varieties: The Microeconomics of High-Yielding Variety Adoption in Malawi." *Economic Development and Cultural Change* 43 (2): 351–368.
- Smale, M., P. Zambrano, G. Gruère, et al. 2009. *Measuring the Economic Impacts of Transgenic Crops in Developing Agriculture during the First Decade: Approaches, Findings, and Future Directions*. Washington, DC: IFPRI.
- Spielman, D.J., and M. Smale. 2017. "Policy Options to Accelerate Varietal Change among Smallholder Farmers in South Asia and Africa South of the Sahara." IFPRI Discussion Paper 1666. Washington, DC: IFPRI.
- Stevenson, J.R., K. Macours, and D. Gollin. 2023. "The Rigor Revolution: New Standards of Evidence for Impact Assessment of International Agricultural Research." *Annual Review of Resource Economics* 15 (1): 495–515.
- Suri, T. 2011. "Selection and Comparative Advantage In Technology Adoption." *Econometrica* 79 (1): 159–209.
- Suri, T., and C. Udry. 2022. "Agricultural Technology in Africa." *Journal of Economic Perspectives* 36 (1): 33–56.
- Taylor, J.E., and Filipski, M.J. 2014. *Beyond Experiments in Development Economics: Local Economy-wide Impact Evaluation*. Oxford: Oxford University Press.
- ter Steeg, E.M.S., and Louwaars, N.P., 2024. "Market-Driven Transitions in the Vegetable Seed Sector in Sub-Saharan Africa," *Agricultural Systems* 221: 104113.
- Trachtman, C., B. Kramer, and J. do Nascimento. 2025. "Market Information and R&D investment under Ambiguity: A Framed Artefactual Experiment with Plant Breeding Professionals." IFPRI Discussion Paper 2314. IFPRI, Washington, DC.
- Tripp, R., and N. Louwaars. 1997. "Seed Regulation: Choices on the Road to Reform." *Food Policy* 22 (5): 433–446.
- Van Campenhout, B. 2021. "The Role of Information in Agricultural Technology Adoption: Experimental Evidence from Rice Farmers in Uganda." *Economic Development and Cultural Change* 69 (3): 1239–1272.

- Van Campenhout, B., D.J. Spielman, and E. Lecoutere. 2021. "Information and Communication Technologies to Provide Agricultural Advice to Smallholder Farmers: Experimental Evidence from Uganda." *American Journal of Agricultural Economics* 103 (1): 317–337.
- Ward, P.S., S. Makhija, and D.J. Spielman. 2020. "Drought-Tolerant Rice, Weather Index Insurance, and Comprehensive Risk Management for Smallholders: Evidence from a Multi-Year Field Experiment in India." *Australian Journal of Agricultural and Resource Economics* 64 (2): 421–454.
- Wellard, K., J. Osando, H. Odame, et al., 2019. *End of Program Evaluation for AGRA Africa's Seed Systems Programs Evaluation: Evaluation Report*. Nairobi: AGRA.
- Weltzien, E., F. Rattunde, A. Christinck, K. Isaacs, and J. Ashby. 2019. "Gender and Farmer Preferences for Varietal Traits: Evidence and Issues for Crop Improvement." *Plant Breeding Reviews* 43: 243–278.
- Wiebe, K., T.B. Sulser, S. Dunston, M.W. Rosegrant, K. Fuglie, D. Willenbockel, and G.C. Nelson. 2021. "Modeling Impacts of Faster Productivity Growth to Inform the CGIAR Initiative on Crops to End Hunger." *PLoS One* 16 (4): e0249994.
- Wollburg, P., T. Bentze, Y. Lu, C. Udry, and D. Gollin. 2024. "Crop Yields Fail to Rise in Smallholder Farming Systems in Sub-Saharan Africa." *PNAS* 121 (21): e2312519121.