



THE TFP GROWTH FRONTIER

PLATEAUS AND PROGRESS IN AGRICULTURAL PRODUCTIVITY GROWTH

2025 GAP Report™

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This report includes short abstracts from our GAP Supporting, Technical, and Research partners describing the work they are doing to improve agricultural productivity around the world. Visit to read the full stories and learn more.



References for the print version of the 2025 GAP Report™ are available online. Scan the QR code or visit: <https://globalagriculturalproductivity.org/2025-gap-report-references/>



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Agricultural systems face converging pressures that make productivity growth—producing the same or more output with fewer inputs—an economic and strategic imperative. Global demand for agricultural products is projected to rise more than 1 percent per year through 2031, driven by population growth, rising incomes, evolving demand, and expanding non-food uses, including biofuels and industrial materials. These demand pressures coincide with tightening resource constraints, ecosystem degradation, lackluster investment in research and development, and geopolitical uncertainty. Against this backdrop, agricultural total factor productivity (TFP) growth has stagnated since 2014. To meet current and future demand sustainably under these conditions and ensure farmer profitability, the tools, strategies, and systems that once fueled decades of efficiency gains must evolve and transform. To do so, investors, policy makers, researchers, and innovators must be able to identify the causes of productivity growth stagnation and implement evidence-based approaches that remove barriers, expand productivity growth ceilings, and shift agricultural systems into new domains.

KEY DATA FINDINGS

-  Global agricultural productivity growth, averaging 0.76 percent annually, is only about one-third of the target rate of 2 percent per year needed to sustainably and profitably meet the demands of our agri-food systems.
-  Asia—particularly China, India, and Vietnam—has emerged as a global productivity leader, driven by sustained R&D investment and technology adoption. By contrast, much of Sub-Saharan Africa and Latin America remain reliant on land expansion and input intensification—strategies that may generate short-term output gains but can also erode ecosystems and stall sustainable growth.
-  While the U.S. averaged -0.05 percent annual TFP growth during the past decade, China surged ahead at 1.9 percent, backed by twice the R&D funding—threatening the U.S.’s edge in global agriculture.
-  In U.S. agriculture, the trajectory of TFP growth is closely tied to macroeconomic conditions. During the 1980s farm crisis, constrained capital pushed TFP growth above 2 percent per year; by contrast, the credit-fueled 1970s and the low-interest-rate 2010s encouraged input-heavy expansion and slowed productivity growth.

THE TFP GROWTH FRONTIER MODEL





The TFP Growth Frontier provides a new way to visualize how productivity gains evolve over time. It maps progress driven by four domains of technologies, practices, and management tactics—each with its own limit on how much productivity growth it can deliver:

-  **Extensification** - Expanding or transitioning agricultural land to boost output.
-  **Input Intensification** - Leveraging fertilizers, improved genetics, and mechanization to drive yield increases.
-  **Efficiency Optimization** - Using digital tools, precision agriculture, and advanced genetics to maximize resource use efficiency and farmer profitability while reducing environmental impacts.
-  **Systems Integration** - Managing agriculture within broader socio- and ecological systems to enhance resilience, sustainability, and multi-functional benefits.

By showing where gaps and inefficiencies exist, the model offers decision makers and investors a strategic lens for portfolio diversification and differentiation. By mapping opportunities along these domains, capital and policy can be directed toward emerging technologies, scalable innovations, and market segments best positioned to drive progress in sustainable productivity growth.

COUNTRY CATEGORIES





Countries sit at different points along the TFP Growth Frontier, reflecting their levels of innovation, adoption, and enabling conditions.

-  **Frontier Leaders**—such as the United States, the Netherlands, and Israel—are on the cutting edge of innovation but risk stagnation due to diminishing returns and underinvestment in public R&D.
-  **Fast Followers**—including India, Brazil, China, and Vietnam—are rapidly adopting proven tools and progressing across multiple domains, driven by strong enabling environments and public-private partnerships.
-  **Potential Leapfroggers**—Rwanda, Costa Rica, and parts of Southeast Asia, for example—have the capacity to bypass earlier stages by adopting advanced tools from later-stage domains when supported by robust digital infrastructure, financing, and governance.
-  **Developing Adopters**—largely in Sub-Saharan Africa and other low-income regions—face persistent adoption gaps due to weak infrastructure, fragmented markets, and limited access to innovation, but hold significant untapped potential for productivity gains.

Understanding these country archetypes helps target investments, partnerships, and policies to accelerate productivity growth where it is needed most.

PATHS FORWARD

To reverse the global productivity slowdown and unlock new levels of productivity growth the report identifies four key strategies:

-  **Scale adoption of proven tools through high-impact bundles** that integrate technology with financing, extension, and infrastructure support.
-  **Push domain frontiers outward via sustained public and private R&D investment**, particularly in underfunded areas such as foundational biology, engineering, and systems integration science.
-  **Facilitate transitions to next-stage domains** by modernizing regulatory frameworks, improving data infrastructure, and aligning policy with innovation.
-  **Enable leapfrogging in emerging economies**, allowing countries with strong digital infrastructure and institutional capacity to skip stages and adopt advanced systems rapidly.

Reinvigorating productivity growth is essential to keeping food and other agricultural products affordable, while raising farm incomes and reducing pressure on environmental systems. The TFP Growth Frontier offers a practical roadmap for governments, industry, researchers, and producers to pinpoint where productivity is plateauing, target the next gains, and align R&D, adoption support, and policy to build a more efficient, resilient, and sustainable agricultural system.

Global demand for agricultural products—including food, feed, fiber, fuel, and industrial raw materials—is shaped by population and income growth, shifting consumer preferences, policy, and expected prices. During the next decade, average consumption is projected to rise by about 1.1 percent per year, with low- and middle-income countries driving 94 percent of this increase. Cereal demand is expected to grow by 11 percent, reaching 3.1 billion tons by 2031, with non-food uses such as industrial fibers and biofuels comprising roughly 20 percent of total use (OECD & FAO, 2024). Protein demand is also growing rapidly. Meat consumption is projected to increase by 15 percent, with feed demand rising faster than direct food use, and aquaculture emerging as one of the fastest-growing food sectors (FAO, 2024; OECD & FAO, 2022).

Meeting these demands will require a deliberate focus on agricultural productivity growth—producing more output with the same or fewer inputs. While expanding the area under cultivation, extending irrigation to existing fields, or intensifying the use of inputs can contribute to agricultural output growth, increasing total factor productivity (TFP) offers a more sustainable way to profitably meet the demands of our agri-food systems.

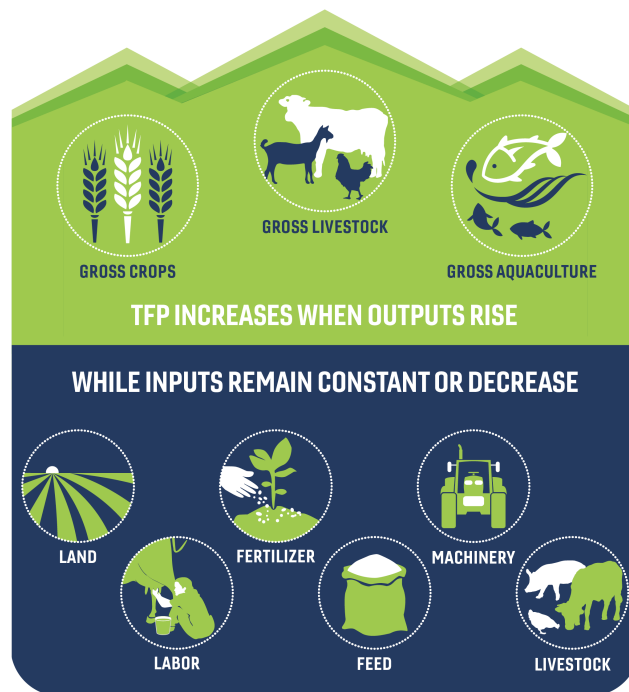
With the right technologies, practices, and policies, productivity growth also generates broad-based returns: higher farm incomes and rural economic growth, improved access to affordable and nutritious food, and more inclusive agricultural systems that support producers at all levels. Importantly, sustainable productivity growth also safeguards the environment by enhancing resource efficiency, reducing greenhouse gas emissions, and preserving biodiversity.

THE CRITICAL ROLE OF TFP GROWTH

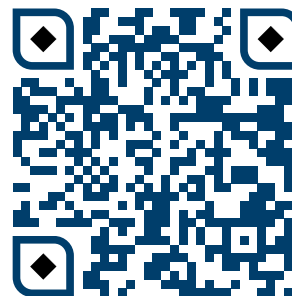
TFP measures how efficiently agricultural resources and inputs—such as land, labor, capital, materials, and feed—are converted into crop, livestock, and aquaculture commodities (Figure 1).¹ An important indicator of system-wide efficiency, it signals how effectively natural, technological, human, and financial resources are being used. **TFP growth occurs either by increasing output using the same or fewer resources or by maintaining output while reducing inputs.**

¹ In 2021, USDA's Economic Research Service incorporated aquaculture into the International Agricultural Productivity dataset, broadening how system-wide efficiency in food production is measured.

Figure 1. Total Factor Productivity (TFP) Growth



WATCH: "The Case for Productivity" on YouTube



These efficiency gains are driven by the adoption of new and proven technologies and practices, improved management, and reallocation of production factors (e.g., land, labor). A robust enabling environment—including sound policies, investment, research and development, and effective extension services—and sustained access to proven productivity-enhancing tools are essential to achieving this adoption.

When achieved sustainably, productivity growth unlocks powerful co-benefits for producers, societies, the economy, and the environment (Fuglie, 2024). However, these gains are neither automatic nor uniformly distributed. Realizing their

full potential requires actively managing trade-offs through adaptive, evidence-based policies and investments, as illustrated in the dynamics of farm income, food security, land use, and environmental impacts.

<p style="text-align: center;">FARM INCOME</p> <p>TFP growth boosts farm income by increasing output and/or reducing production costs. However, economies of scale influence the ability of farms of various sizes to capture benefits. Input subsidies, extension services, environmental regulations, and innovation investments all shape the path from productivity to profit. Market dynamics also count—global price volatility plays a central role in producer profitability.</p>	<p style="text-align: center;">FOOD SECURITY</p> <p>TFP growth improves food security through lower food prices and higher incomes. Yet, if policies fail to address system and market failures, then distribution inefficiencies, food loss and waste, income dynamics, and socio-economic inequalities may prevent improved productivity growth from contributing to improved food security.</p>
<p style="text-align: center;">LAND USE</p> <p>TFP growth inherently supports land conservation by enabling higher output from existing agricultural land. This is vital for biodiversity protection and conservation. Nevertheless, there is some evidence to suggest that higher productivity can drive short-term land expansion, especially in income inequality contexts, or lead to spared land being lost to other development pressures (Ceddia, 2019; McIntosh, 2024)</p>	<p style="text-align: center;">ENVIRONMENTAL PROTECTION</p> <p>TFP growth can help lower emissions, improve water use, and minimize environmental impacts by using advanced technologies and practices rather than intensify input use. However, environmental outcomes depend on how productivity gains are achieved and whether they are coupled with environmental safeguards. While trade-offs exist, there are technological and policy solutions that can bring balance to agricultural and environmental systems.</p>

TFP GROWTH TRENDS

To track productivity growth progress, the Global Agricultural Productivity (GAP) Index was introduced in 2010. The original target of 1.73 percent average annual TFP growth (2010-2050) reflected the need to double agricultural output for a projected 2050 population of 10 billion while limiting agriculture’s geographic and ecological footprint to 2010 levels by relying predominantly on productivity gains (solid green line, Figure 2).

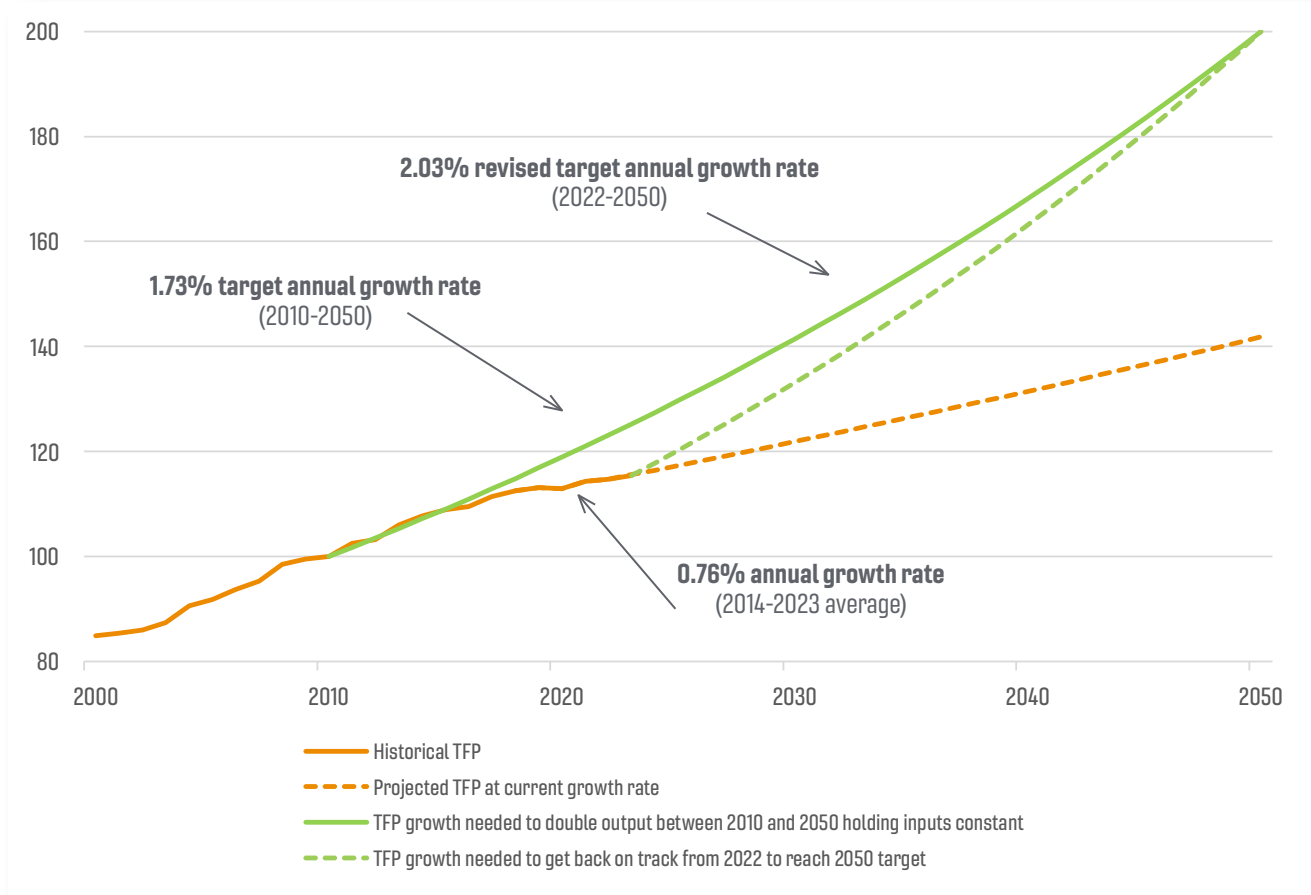
Although population growth is now slowing (United Nations, 2024), pressures on agricultural systems remain high due to rising incomes, shifting consumption patterns, and expanding non-food demand. While there is no explicit accounting for income, dietary, or climate impacts in the GAP Index, growing demand drivers reaffirm the need for sustained, inclusive productivity growth. The GAP Index serves as a key benchmark for measuring this progress and aligning innovation, policy, and investment with long-term sustainability across the agri-food system.

The slowdown in global TFP growth—averaging just 0.76 percent annually between 2014 and 2023 (orange line, Figure 2)—signals a critical need to reinvigorate progress. To sustainably meet growing and evolving global demand while safeguarding natural resources and improving livelihoods, productivity growth must now average 2.03 percent annually from 2025 to 2050 (dashed green line, Figure 2).

The deceleration in global TFP growth between 2014 and 2023 marks a clear break from the previous 25 years, when productivity gains were the primary driver of agricultural output growth (Figure 3). During this most recent period, annual growth averaged just 0.76 percent, down from 1.16 percent during 2011-2020. This confirms a consistent downward trend, falling 60 percent from peak TFP growth during the 2000s. This signals that structural factors—such as lagging R&D investment, slower technology adoption, and mounting climate pressures—are constraining system-wide efficiency gains.

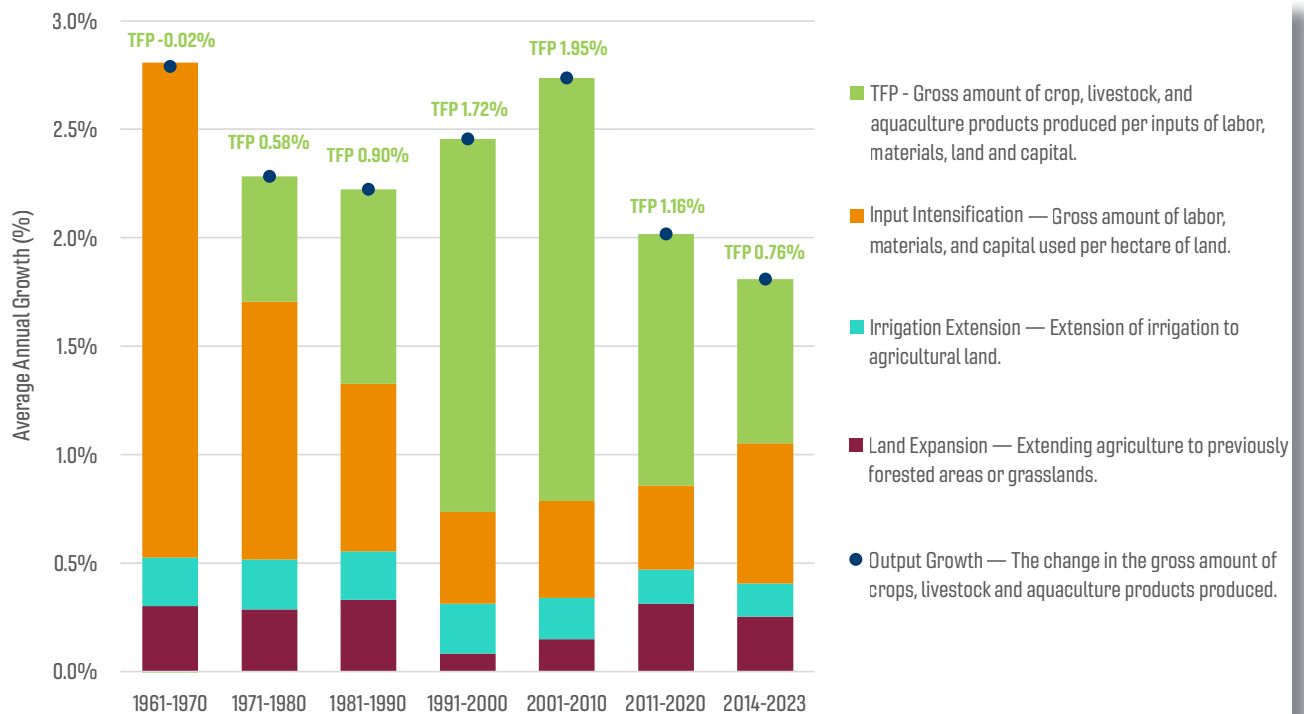
Figure 2.
2025 GLOBAL AGRICULTURAL PRODUCTIVITY INDEX

TFP growth rates are based on a ten-year rolling average



Source: Fuglie, 2025.

Figure 3. Global Sources of Agricultural Output Growth, 1961-2023



Source: Fuglie, 2025.

REGIONAL TRENDS AND LEADING COUNTRIES

Despite the global slowdown, TFP growth was far from uniform during the past decade. While some regions relied heavily on land expansion and inputs, others achieved substantial efficiency gains.

ASIA emerged as a global leader, particularly countries in the northeast and south (Figure 4). Northeast Asia fell just below the target growth rate, averaging 1.9 percent TFP growth annually. Notably, nearly 2 percent output growth was achieved without increasing input use and with a 0.2 average annual reduction in farmland. China led the region in productivity gains, driven by mechanization (Cui, 2023; Li & Guan, 2023; Lu et al., 2024), more sustainable input practices (OECD, 2018), and major public investment in agricultural R&D (Plastina & Townsend, 2023; van Dijk et al., 2025). China now spends more than twice as much on agricultural R&D as the United States (Nelson & Fuglie, 2022a).

South Asia ranked second at 1.48 percent average annual TFP growth, led by India (1.59 percent) and Pakistan (1.74 percent), with growth fueled by technology adoption, mechanization, labor shifts, and increased ICT use (Liu et al., 2020). India's rise reflects its position as one of the world's top 10 public agricultural R&D investors (van Dijk et al., 2025). South Asia's robust average annual output growth of 3.5 percent was supported by increased input use and irrigation expansion along with TFP growth.

Southeast Asia and the Pacific had the lowest TFP growth rate for the continent, averaging 1.04 percent annually. However, within the region, Vietnam and Indonesia stood out as global leaders, averaging 2.81 percent and 1.5 percent annual TFP growth respectively during 2014-2023, deriving gains from technological progress, management improvements, and structural transition toward high-value production systems, supported by strong markets (H. Q. Nguyen, 2021; T. L. Nguyen et al., 2025; OECD, 2023).

EFFICIENCY OPTIMIZATION

A New Chapter For Wheat: Innovation to Meet Global Demand Corteva Agriscience



Photo: Corteva Agriscience

Wheat is the world's most widely grown crop, cultivated on over 215 million hectares and providing 20% of global protein and caloric intake (CIMMYT). However, global wheat production has declined in recent years due to climate stress and agronomic limitations. At the same time, nearly one-third of the global population remains food insecure, highlighting the urgent need for more resilient and productive cropping systems. One of the ways Corteva Agriscience is addressing this challenge is through its hybrid wheat program, which combines advanced breeding with scalable seed production. With a consistent double-digit yield advantage over conventional varieties tested in R&D plots, hybrid wheat could potentially allow farmers to produce more on existing farmland—while improving resilience in drought conditions. By drawing on experience in hybrid corn and integrating digital tools and agronomic support, Corteva is working to deliver a hybrid wheat product to help farmers improve productivity and profitability. With a U.S. launch planned for 2027, hybrid wheat represents a critical step toward accelerating innovations to feed the world.

EFFICIENCY OPTIMIZATION

Ancient Grain, Modern Innovation: How Gene Editing Strengthens Ethiopia's Teff Harvest Corteva Agriscience

Teff is a vital crop in Ethiopia, providing up to two-thirds of the country's protein and dietary fiber. Though central to Ethiopian identity, nutrition, and rural livelihoods, teff cultivation remains labor-intensive and vulnerable to agronomic challenges like lodging, which reduces yields and marketability. Corteva, in collaboration with the Ethiopian Institute of Agricultural Research and the Donald Danforth Plant Science Center, applied gene-editing technologies to develop shorter and sturdier teff varieties that can stand up to strong winds. This innovation, now supported by the Bill & Melinda Gates Foundation, aims to reduce lodging-related yield losses by up to 25%, ease labor demands, and enhance both productivity and nutritional composition. Accelerating this innovation to smallholder farmers will help improve the production of a crop which is key to feeding the world.



Photo: Donald Danforth Plant Science Center

THE CENTRAL AND WEST ASIA AND NORTH AFRICA (CWANA) region, which includes Turkey, Iraq, Saudi Arabia, Morocco, Egypt, Iran, Kazakhstan, and Uzbekistan, is characterized by arid climates. Despite challenges in water availability, climatic variability, and geopolitics, TFP growth was the main driver of output growth, averaging 1.19 percent annually. This was complemented by modest growth in input use and irrigation extension.

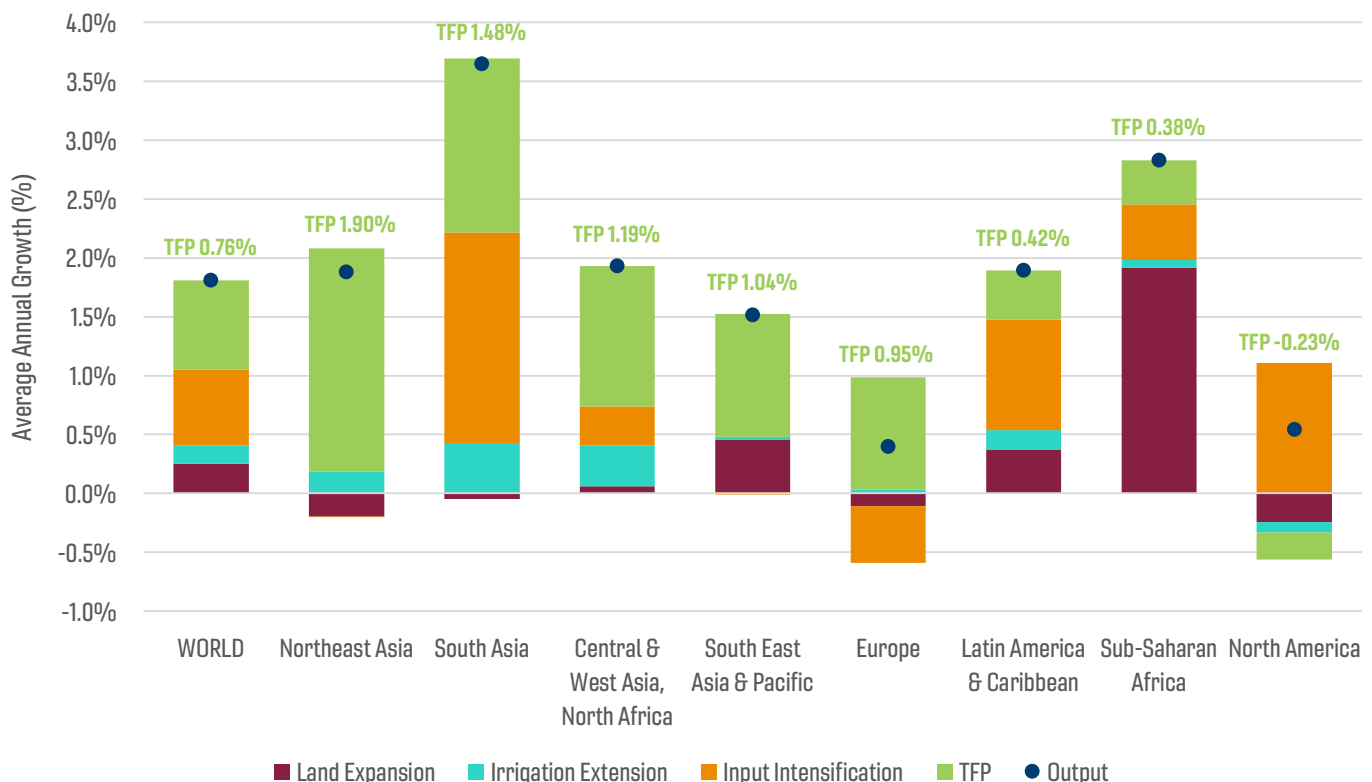
EUROPE fell just short of 1 percent average annual TFP growth. This was largely driven by increases in labor productivity and reallocating resources to more productive operations. Between 2010 and 2020, the number of farms fell by about 3 million (Boccaletti et al., 2024). Progress in efficiency gains was not sufficient to make up for the contraction in farmland and input use, causing output growth to fall to less than an average 0.5 percent annually.

LATIN AMERICA AND THE CARIBBEAN experienced robust agricultural output growth during this period; however, this was primarily achieved through growth in input use (0.94 percent) and modest land expansion (0.37 percent). TFP growth, meanwhile, only averaged 0.42 percent annually. This was largely due to lagging progress in labor productivity and changes in the policy environment, which favored input-heavy growth but reduced investment in public R&D (CAF, 2025).

SUB-SAHARAN AFRICA continued to experience lagging productivity gains, averaging 0.38 percent TFP growth annually. A noteworthy output growth rate, averaging almost 3 percent per year, was primarily driven by land expansion and input intensification, as limited technological adoption and underinvestment in agricultural R&D constrained productivity gains. Fertilizer use continues to increase in SSA, but the average application rate across all croplands is only 21 kg NPK per hectare, far lower than necessary (Fuglie, 2025). The challenges of low input rates and low productivity growth, compounded by the impacts of climate variability (Ortiz-Bobea et al., 2021), have led to widespread land conversion at an alarming rate, with negative effects on biodiversity (Koch et al., 2019).

NORTH AMERICA has experienced a historic low in TFP growth, averaging -0.23 percent annually over the last decade. While input use has increased, contracting TFP growth and land use have caused output growth to fall to historic lows of an average of 0.5 percent annually. This trend underscores the long-term consequences of underinvestment in public agricultural R&D and persistent bottlenecks in the innovation-to-adoption pipeline (Nelson & Fuglie, 2022b).

Figure 4. Sources of Agricultural Output Growth by Region, 2014-2023



Source: Fuglie, 2025.

TRENDS BY COUNTRY INCOME LEVEL

These regional differences reveal a broader trend related to country income levels (Figure 5). Low-income countries—including much of Sub-Saharan Africa—are relying on sources of output growth that may be unsustainable and have negative impacts on farmer livelihoods and environmental resources. High output growth (2.64 percent annually) is driven by land expansion (1.65 percent) and input intensification (1.5 percent); meanwhile, TFP growth averaged -0.56 percent annually.

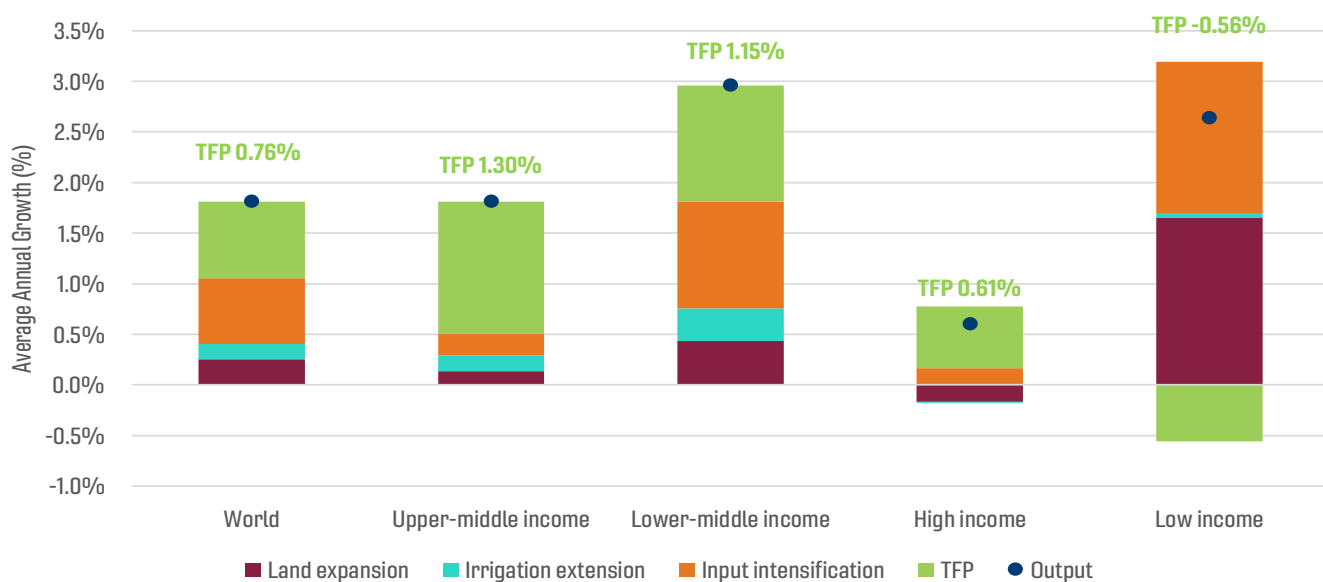
By contrast, upper-middle-income countries such as China and much of Southeast Asia are achieving relatively robust annual output growth (1.81 percent) with substantial TFP gains (1.30 percent) and slight land expansion (0.14 percent). Lower-middle-income countries, such as India and Pakistan, are transitioning to more efficient production systems (1.15 percent TFP growth) but still rely on input intensification combined with modest land expansion (0.44 percent) and irrigation extension (0.32 percent).

High-income countries illustrate the paradox of technological maturity. Although TFP gains remain the primary driver of agricultural output growth (0.61 percent), the plateauing of productivity gains—combined with stable input use and the gradual contraction of farmland—has led to a marked slowdown in overall output expansion (now only 0.56 percent annually). This trend reflects the maturing limits of past innovations and highlights the need for new approaches to sustain TFP growth.

During the past decade, trends in agricultural productivity growth have revealed both promising opportunities and critical vulnerabilities in today’s agri-food systems. Global output has continued to rise—growing by about 1.7 percent annually—but too much of that growth still depends on land expansion and input intensification, particularly in low-income regions of Sub-Saharan Africa and parts of Latin America. Meanwhile, global TFP growth is only one-third the rate required to sustainably meet mid-century demand.

Unlocking a new era of productivity growth will require a deeper understanding of the causes of productivity plateaus, along with models to identify where innovation, adoption, and system transformation can drive the next wave of progress.

Figure 5. Sources of Agricultural Output Growth by Income Group, 2014-2023



Source: Fuglie, 2025.

The past decade's plateau in TFP growth underscores the scale of the global agricultural productivity challenge, but it does not explain why growth has slowed, nor how to reinvigorate it. To chart a path forward, we must better understand the forces driving and constraining productivity growth across different contexts.

Sustainably and profitably maintaining output growth by limiting the growth of input use requires ongoing technological innovation, improved practices, and better management. As adoption of an individual technology increases, it will eventually contribute less to productivity growth (Schumpeter, 1976). Long-run TFP growth, therefore, depends not just on the diffusion of existing tools but also on the continuous development and adoption of new ones (Romer, 1986; Solow, 1956).

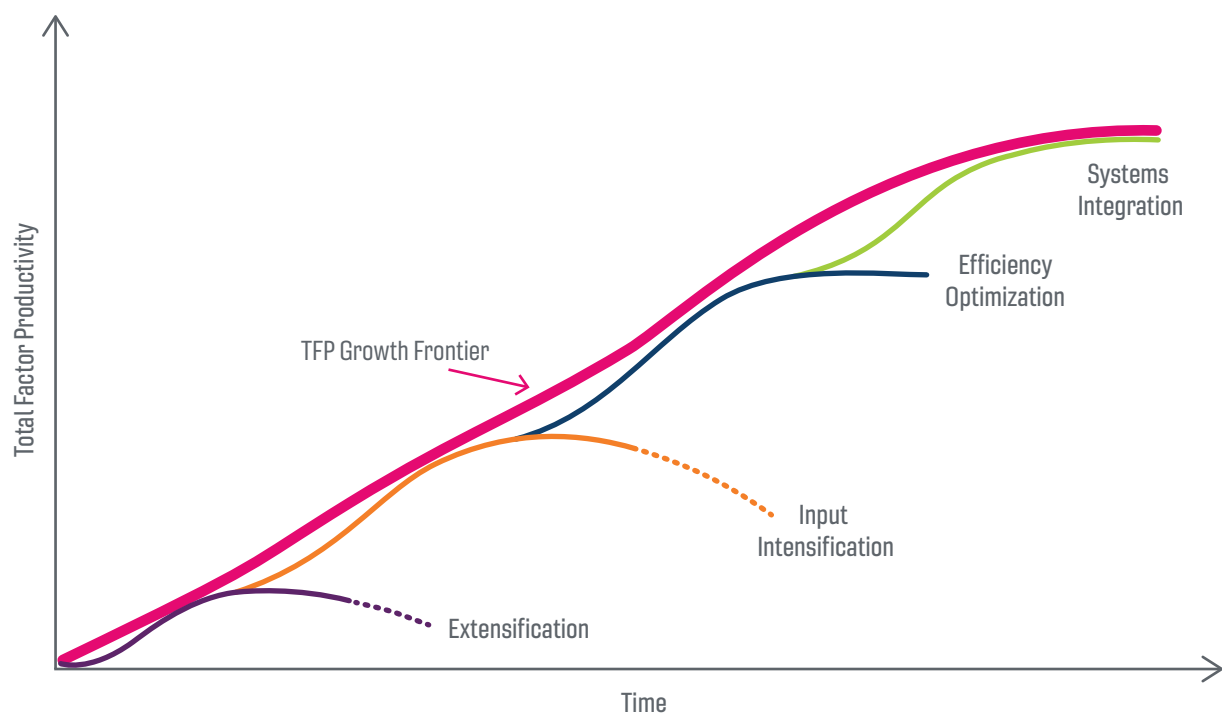
The **TFP Growth Frontier**—a novel conceptual model that visualizes overall, long-run productivity growth achieved through a sequence of **technological domains**—diagnoses these dynamics and guides strategic action to reinvigorate productivity growth. The model serves as a benchmark for measuring and comparing inefficiencies, adoption lags, and performance gaps, and illuminates opportunities to drive productivity progress within and across agricultural systems.

The TFP Growth Frontier comprises four technological domains:

- 1 **Extensification:** expanding or transitioning agricultural land to boost output.
- 2 **Input Intensification:** increasing output on the same lands by increasing input use.
- 3 **Efficiency Optimization:** maximizing resource use efficiency to minimize environmental impact and ensure farmer profitability.
- 4 **Systems Integration:** harmonizing production across socio-ecological systems.

Each domain frontier illustrates how the productivity growth ceiling changes over time; eventually, growth slows or may even decline (purple, orange, blue, and green lines, Figure 6). Together, these domain frontiers form the TFP Growth Frontier (shown as the magenta outer envelope in Figure 6), which captures the long-run trajectory of productivity growth. These domains tend to overlap rather than follow a strict sequence or fully replacing earlier frontiers.

Figure 6. TFP Growth Frontier





Productivity-enhancing tools: Technologies, practices, and management techniques used to increase or maintain output while reducing inputs.



Frontier: The maximum achievable TFP growth based on existing productivity-enhancing tools.



Technological domain: The prevailing ideas, values, innovation models, and external forces that shape the development of productivity-enhancing tools.



Domain frontier: The domain-specific TFP growth ceiling—the potential TFP growth achievable based on the domain's available tools.



TFP Growth Frontier: The long-run, system-wide limit that envelopes all past, present, and future frontiers.

FOUR TECHNOLOGICAL DOMAINS OF AGRICULTURAL PRODUCTIVITY GROWTH

The emergence and evolution of technological domains have been shaped by farm-level needs, public and private R&D priorities, policy frameworks, external forces, and societal objectives. Farm-level pressures and innovation often signal a need for subsequent technological development. Public and private R&D investments respond to these signals by creating tools that can raise productivity ceilings. Policy frameworks and macroeconomic conditions—such as access to credit, input subsidies, trade policies, and infrastructure investments—can accelerate or constrain the adoption of new technologies. At the same time, technological evolution is increasingly driven by external pressures—including shifting market demands, global trade dynamics, and extreme weather events—that require a response. Societal priorities, such as environmental sustainability, food security, and climate resilience, further shape which innovations are pursued and how they are implemented. As the agricultural sector develops, these forces converge to form four unique technological domains that influence the pace and distribution of productivity growth.

EXTENSIFICATION

The Extensification domain, often first to emerge in newly developing agricultural systems, establishes a functional sector by bringing new lands into production, expanding labor use, and introducing basic inputs. This domain is enabled by abundant

arable land, low population density, and limited capital. Throughout most of human history, extensification has been the dominant strategy for increasing agricultural output when the sector is first emerging.

Technological innovations emerge to support land expansion efficiency, labor productivity, and early-stage market integration. In 19th-century North America, for example, mechanical reapers boosted labor productivity, while railroad-linked grain storage systems created incentives for greater productivity investment (Rhodes, 2016).

Land-use conversion, such as shifting pasture land to cropland, is also a hallmark of this domain. While the land is already in agricultural use, conversion can expand higher-intensity production, increasing total cultivated area rather than driving efficiency gains on existing cropland. In Brazil's Cerrado, for instance, large-scale conversion of pasture into soybean and maize fields during the past two decades fueled significant output growth, supported by basic mechanization but with limited optimization of input use (Zalles et al., 2019).

As population density increases and environmental resource pressures intensify, the limits of the Extensification domain become evident. Minimal TFP growth stagnates quickly. The conversion of forests and grasslands to agricultural land contributes to biodiversity loss and degrades soils and ecosystems, ultimately putting output gains at risk. Today, much of sub-Saharan Africa still operates within the Extensification domain; approximately 4.7 million hectares of land are brought into agricultural production each year

(Fuglie, 2025). As Figure 4 shows, land expansion for agriculture in sub-Saharan Africa grew by an average of nearly 2 percent per year from 2014 to 2023.

Core domain objective: Establish a viable agricultural sector.

Examples of Domain Innovations: Basic mechanization (plows, early tractor technology, reapers), minimal chemical inputs, basic irrigation systems.

Domain KPIs: Agricultural output, acres in production, basic labor productivity.

Plateau Signals

- Output continues to grow mainly by increasing land under cultivation, while yields and TFP growth stagnate.
- The cost of bringing new land into production rises.
- Labor productivity stalls.
- Growing reliance on subsidies and credit to sustain incomes and growth rates.
- Land productivity may decrease as soil resources are exhausted.

INPUT INTENSIFICATION

The Input Intensification domain emerges in response to limited land availability and the environmental impacts of expanding into new lands, coupled with rising agricultural demand and the need for producer profitability. The Green Revolution embodies this domain, introducing high-

yielding varieties, synthetic fertilizers, pesticides, and irrigation systems (Pingali, 2012).

Depending on the enabling environment, TFP growth under this domain can be rapid. These productivity-enhancing tools tend to be adopted quickly, especially if subsidies or affordable financing are available, since producers easily observe improved yields and attain higher incomes. These inputs also tend to be relatively affordable.

In many advanced agricultural systems, the Input Intensification domain frontier has matured. Yield plateaus are now common, and in some cases, maintaining previous output gains requires heavier input use. In the U.S. Corn Belt, for example, yield growth from hybrid seeds, precision planting, and optimized fertilizer use has slowed, with higher nitrogen applications and more intensive crop protection needed just to sustain current production. These shifts heighten environmental trade-offs—such as groundwater depletion, soil nutrient loss, and pesticide resistance—while rising input costs and shrinking margins add mounting economic pressures for producers.

By contrast, smallholder producers in emerging economies face persistent barriers to adopting Input Intensification tools, deepening regional inequalities. Although this frontier has matured globally, TFP and output growth can still be increased in lower-resource contexts by increasing the appropriate adoption of these foundational technologies, practices, and management strategies.



Photo: CIP

INPUT INTENSIFICATION

Speeding New Potato Varieties to Farmers: How Apical Rooted Cuttings are Transforming the Seed Sector in the Global South

International Potato Center (CIP)

A breakthrough method known as apical rooted cuttings (ARC) is transforming both the speed and economics of delivering improved potato varieties to farmers in India and Africa. The International Potato Center (CIP), which introduced ARC to India in 2019, is already seeing promising results. Traditional seed systems delay farmers' access to genetic gains by six years or more. However, ARC cuts that lag to just two years, giving farmers three times more opportunity to capture productivity improvements in their fields. By reducing seed costs, from nearly half of the production expenses to a much smaller share, ARC raises net profits or frees up capital for reinvestment in fertilizers, improved irrigation, or other yield-enhancing inputs. Local multiplication of disease-free, physiologically optimal cuttings further eliminates transport-related losses. Farmers report significant yield improvements and more consistent production across seasons, demonstrating that ARC is not merely a technology for faster seed delivery but a powerful solution to help farmers produce more with less time, money, and risk.



EFFICIENCY OPTIMIZATION

Agricultural Productivity Growth with Efficient Optimization

The S M Sehgal Foundation (SMSF)

Small and marginal farmers in rural India cultivate the land that feeds a nation, yet their futures remain uncertain. With shrinking plots and ever-growing climate challenges, they need smart, resource-efficient, and scalable productivity-enhancing solutions. The Sehgal Foundation works to enhance agricultural productivity with efficient optimization of water, soil, and input use, through tools that focus on the specific needs of small and marginal farmers. By promoting low-cost technology such as drip and sprinkler irrigation, communities are learning to use water resources effectively. Field practices include the judicious use of chemicals, liquid and compound fertilizers, and more-effective nutrient blends tailored to local soil conditions. The introduction of biochar, a low-cost soil enhancer, improves soil structure and moisture retention to further advance total farm productivity.

Photos: Sehgal Foundation



Core domain objective: Meet rising agricultural demand of a growing population.

Examples of Domain Innovations: Improved genetics (e.g., high yielding varieties), synthetic fertilizers, pesticides, controlled irrigation systems, advanced mechanization (tractors, threshers, pumps).

Domain KPIs: Yield per acre, input use and responsiveness, changes in acreage, water productivity.

Plateau Signals

- Yield gains flatten as input use increases (diminishing returns).
- Pest, weed, and disease resistance escalates, requiring more or new chemistries.
- Soil and water degradation (runoff, salinization, acidification) reduces input responsiveness.
- Rising input and compliance costs squeeze margins; subsidies required to sustain growth.

EFFICIENCY OPTIMIZATION

The Efficiency Optimization domain arises as a response to the environmental and economic limitations of the Input Intensification domain. The core objective is advancing sustainable intensification by enhancing the efficiency of resource use—land, water, energy, and inputs—while maintaining or increasing output, minimizing environmental impact, and ensuring that farmers are profitable.

Technological innovation in this domain focuses on fine-tuning input use across different conditions and time frames, driving greater efficiency, lowering costs, and easing pressure on natural resources.

Breakthroughs in digital agriculture and genetics are creating substantial productivity gains that are nowhere near exhausted. Highly effective decision-support systems and management software are using cutting-edge tools that collect and leverage data to improve practices, management, and productivity. Precision agriculture—supported by GPS-enabled machinery, drones, and Internet of Things (IoT) sensors—enables real-time monitoring of soil and crop conditions for site-specific input application. Gene editing technologies, such as CRISPR, offer additional productivity gains by developing crops and livestock genetics that are more resilient to environmental stressors and tailored to specific production conditions without relying on transgenic modifications. Artificial intelligence and machine learning complement both digital and genetic tools by creating the potential to interpret the vast amounts of data generated in modern production.

The Efficiency Optimization domain is steadily advancing, with no sign of stagnation. Innovation is marching steadily forward, and substantial R&D investment continues. However, productivity gains within this domain are unevenly distributed. Adoption barriers are significant due to high upfront costs, technical complexity, and digital infrastructure constraints. In emerging economies, these challenges are magnified by a lack of enabling environments and weak extension systems.

Although the global precision agriculture market is projected to grow rapidly—from \$9.3 billion in 2024 to over \$21 billion by 2033 (IMARC Group, 2024)—TFP growth at the sectoral level may begin to plateau if adoption lags behind innovation. Furthermore, concerns around data privacy, interoperability, and equity in access raise questions about the long-term inclusivity and scalability of this domain.



Photo: ICARDA

EFFICIENCY OPTIMIZATION

Intensifying Cropping Systems with Double-Legume Relay Intercropping in Mediterranean Rainfed Drylands: Insights from Morocco

International Center for Agricultural Research in the Dry Areas (ICARDA)

In Morocco's semi-arid regions, increasing drought and erratic rainfall threaten cereal production and farmer livelihoods. To improve resilience, ICARDA introduced a relay intercropping system, planting chickpeas between paired lentil rows during flowering. This innovation doubled land use efficiency without reducing lentil yields and increasing chickpea yields by 0.8–1.3 t/ha, boosting farm profitability. The system also improves soil fertility through nitrogen fixation, extends soil cover to prevent degradation, and enhances resilience by diversifying crops. Notably, wheat yields following intercropping increased by 8–10%, and protein output improved compared to conventional cereal rotations, offering a climate-smart alternative for vulnerable farming systems.

Core domain objective: Producer profitability, reduced environmental impact.

Examples of Domain Innovations: Precision agriculture, gene editing technologies, decision-support tools, artificial intelligence.

Domain KPIs: Resource efficiency, input-output ratios, soil and water quality, profit margins.

Plateau Signals

- Technology costs outpace efficiency benefits.
- Biophysical and environmental limits are reached.
- Adoption is near saturation with limited new innovations emerging and dry R&D pipelines.

SYSTEMS INTEGRATION

The newly developing Systems Integration domain represents a highly complex approach to sustainable agricultural productivity growth. It recognizes agriculture as part of larger socio- and ecological systems and seeks to align productivity growth with resilience, equity, and environmental sustainability. Unlike other domains, Systems Integration is not centered on discrete technologies but rather on building suites of tools that enable coordinated management across multiple, interacting systems. Current approaches include integrated crop-livestock systems, agroforestry, aquaponics, circular nutrient flows, and ecosystem services markets. Increasingly, resilience and multi-functionality—measured through metrics such as yield stability, biodiversity preservation, and greenhouse gas emissions per unit of output—are

seen as complementary to productivity growth rather than in competition with it.

However, this domain faces significant implementation challenges, including fragmented R&D investments and underdeveloped frameworks for measuring multifunctional outcomes. Adoption of Systems Integration tools is constrained by a lack of incentives and de-risking mechanisms for producers. For example, while carbon credit markets aim to remunerate producers for transitioning to more climate-smart practices, the lack of mature policy frameworks and monitoring, reporting, and verification tools is stagnating progress.

Realizing the Systems Integration domain's potential for TFP growth will require functioning ecosystem services markets and other programs that reward producers for delivering public goods—such as improved soil health, water quality, and biodiversity—alongside innovative productivity-enhancing tools designed to operate across systems. One example is the Alliance to Advance Climate Smart Agriculture, led by Virginia Tech, that is testing a model for incentivizing producers to adopt climate-smart practices across four states.

Careful policy calibration will be required to avoid unintended consequences, such as compromised producer livelihoods, constrained rural economic growth, reduced food and nutrition security, or barriers to youth participation in agriculture. Investment in more effective incentives, innovative financing, research, and coordinated policy frameworks could unlock scalable solutions that advance productivity growth alongside resilience and sustainability.

SYSTEMS INTEGRATION

Breaking Through Plateaus: Ignite+ and the Productivity Promise of Gender and Nutrition Integration

Tanager International

Across sub-Saharan Africa, agricultural productivity growth remains constrained by systemic gender inequality and poor nutrition—factors that, when overlooked, deepen existing disparities and further limit growth. Since 2018, Tanager International's IGNITE initiative has supported over 35 African agriculture institutions to address these barriers by integrating gender and nutrition considerations across their policies, programs, and operations. Now in its second phase, IGNITE+ is deepening systems impact by strengthening local capacity and shifting service delivery ownership directly to African actors. The integrated system aligns gender and nutrition goals within institutional strategies to design more inclusive, effective interventions that improve adoption and drive productivity growth. By positioning local institutions to drive demand for and delivery of technical assistance services at scale, IGNITE+ is demonstrating how investing in integrated approaches leads to better outcomes and fosters more productive, resilient, and equitable agricultural systems.



Photo: Tanager International

Core domain objective: Holistic optimization across multiple systems, leveraging circular resource flows.

Examples of Domain Innovations: Integrated crop-livestock systems, agroforestry, aquaponics, circular nutrient flows, ecosystem services.

Domain KPIs: Ecosystem services value, yield stability, biodiversity metrics, resilience metrics (e.g., yield under stress), carbon footprint per output, multifunctional land productivity.

Plateau Signals

- Coordination cost outweighs benefits
- Synergistic effects between sectors reached maximum
- Ecosystem services markets mature with diminishing premiums

FOUR WAYS TO DRIVE PROGRESS IN TFP GROWTH

The TFP Growth Frontier model reveals four ways to reinvigorate plateauing productivity growth.

1 **SCALE ADOPTION OF A DOMAIN'S PRODUCTIVITY-ENHANCING TOOLS THROUGH HIGH-IMPACT BUNDLES**

TFP growth can plateau when proven productivity-enhancing tools are not adopted. Promising innovations can often stall in the “valley of death”—the critical gap between R&D development and widespread use. This gap arises from limited access, inadequate knowledge transfer, or insufficient financing and incentives. While adoption gaps exist across all domains and regions, they are especially severe in low- and middle-income countries. In sub-Saharan Africa, for example, two-thirds of farmers report no use of inorganic

There are currently technologies in development that hold out promise of significant advancements in productivity growth. Gene editing of crops and livestock is one such technology. Several GE crop varieties are already on the market, with traits that could improve consumer acceptance, shelf life, or industrial use. In May 2025, the government of India approved the release of two gene-edited rice varieties, developed using CRISPR-Cas9, with potential for higher yields, lower greenhouse gas emissions, and improved tolerance to drought, salinity, and climate stresses (Priyadarshini, 2025). Advances in machine learning and artificial intelligence also have huge potential for increasing efficiency in agriculture, especially by helping interpret data generated through yield monitors and sensors, and by increasing application efficiency of inputs such as seeds, fertilizers, and pesticides. We should be concerned, however, with ensuring that such tools can also benefit small- and medium-scale producers.

fertilizers (Sheahan & Barrett, 2017), leaving the region’s production systems well below the Input Intensification domain’s frontier (Point A, Figure 7, p. 16). Closing this gap requires high-impact bundles that integrate productivity-enhancing tools with targeted distribution models, socio-economic interventions, and policy support to accelerate adoption and unlock latent TFP growth potential (see the 2024 GAP Report™).

2 PUSH THE DOMAIN FRONTIER OUTWARD THROUGH R&D

Strategic and sustained public and private R&D investment—supported by strong innovation ecosystems and effective feedback loops among science, policy, and producers—can raise a domain frontier’s productivity ceiling by generating new technologies and practices (dotted blue line, Figure 7). These investments are valuable at any stage of a domain’s development. When an early-stage

EFFICIENCY OPTIMIZATION

Growing More with Less: Mosaic’s Integrated Approach to Sustainable Crop Nutrition Mosaic

The Mosaic Company is advancing global agricultural productivity through a farmer-focused approach that integrates 4R Nutrient Stewardship with cutting-edge crop nutrition and bioscience innovations. By applying the Right Source of nutrients at the Right Rate, Right Time and Right Place, Mosaic supports producers in maximizing fertilizer efficiency, improving yields and protecting environmental resources. With a broad portfolio of products like MicroEssentials® and BioPath®, and partnerships spanning 25 projects with 18 organizations, Mosaic empowers farmers with the tools, knowledge and support to boost profitability and soil health. This integrated strategy strengthens climate resilience and proves that sustainable intensification can align productivity with environmental responsibility.

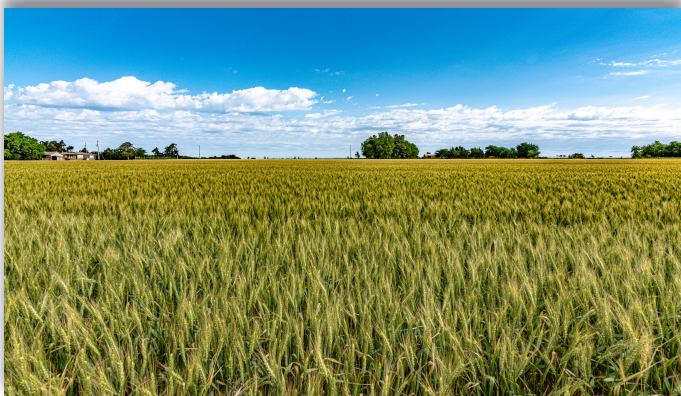


Photo: Mosaic

frontier matures—adoption nears saturation and TFP growth slows—new scientific insights or advanced techniques can push that frontier outward, creating fresh opportunities for productivity gains (dotted pink line, Figure 7). Notably, the Efficiency Optimization and Systems Integration domain frontiers continue to advance, showing no signs that the limits of innovation in these areas have yet been reached.

3 TRANSITION TO THE NEXT DOMAIN FRONTIER

Signals of domain maturity or external pressures, such as increasing climate variability or shifting market demands, can also indicate the need to advance to the next domain (Figure 7). Successful transitions require clear priorities. Where the necessary technologies do not yet exist, the focus should be on building strong investment frameworks and fostering scientific collaboration to ensure that emerging innovations align with producer needs and drive income growth through sustainable productivity gains. Where next-domain



RESEARCH

Beyond One-Size-Fits-All: Targeting Subsidies With Natural Capital Insights The Nature Conservancy

A global analysis of 25 years of data across 15,376 regions in 49 countries, conducted by Virginia Tech and The Nature Conservancy (TNC), demonstrates that the impact of agricultural subsidies on productivity depends critically on local agroecological conditions and the state of natural capital. Decoupled subsidies are associated with modest reductions in yield gaps globally (about 0.5% per 10% increase). However, in regions with high soil moisture capacity or dense vegetative cover—key indicators of natural capital—input and output-based subsidies can have the opposite effect, accelerating degradation and widening yield gaps. By contrast, investments that protect natural capital, particularly measures that preserve soil moisture, consistently deliver the largest productivity gains, reducing yield gaps by up to 14% per 10% increase in investment. The findings highlight a critical principle for advancing TFP growth: when subsidies erode natural capital, they undermine yields, but when subsidies and investments work with nature, they strengthen productivity and system-wide resilience.

Research by Nicolas Legrand and Jason Grant, Virginia Tech

technologies are already available or beginning to surface, priorities shift toward innovating business models, strengthening public and private extension systems, designing supportive policies, and addressing behavioral factors such as skills development and willingness to pay to accelerate adoption. In both scenarios, the transition demands a rethinking of resource allocation and the organization of agricultural systems to unlock sustained TFP growth.

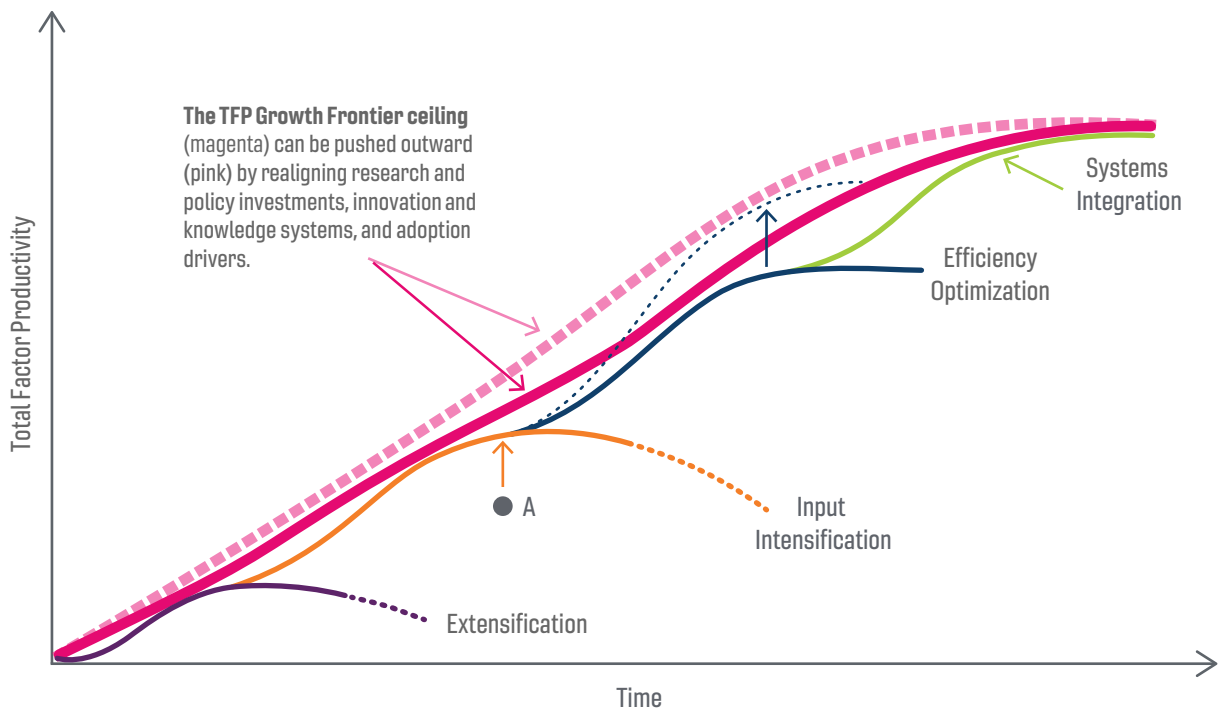
4 LEAP DIRECTLY TO LATER-STAGE DOMAIN FRONTIERS

Some countries are still operating in the Extensification or Input Intensification domains, as shown in Chapter 1. Progressing through each domain in a strict sequence is not always necessary for agricultural development or robust TFP growth. With the right enabling conditions—such as strong digital infrastructure, coordinated institutions, and access to financing—leapfrogging directly to later-stage domains is feasible. In parts of India,

for instance, the rapid growth of smartphone coverage, mobile-based advisory platforms, and digital marketplaces has allowed even smallholder producers to adopt precision irrigation, drone-based crop monitoring, and data-driven input management without decades of intermediate mechanization. When these shifts are supported by strong agricultural knowledge and innovation systems, they can accelerate the adoption of cutting-edge tools and deliver transformative gains in productivity.

The four domains of agricultural productivity growth—Extensification, Input Intensification, Efficiency Optimization, and System Integration—offer decision-makers and investors a strategic lens for portfolio diversification and differentiation. By mapping opportunities along these domains, capital and policy can be directed toward emerging technologies, scalable innovations, and market segments best positioned to drive progress in sustainable productivity growth.

Figure 7. Changes to the TFP Growth Frontier Model



FRONTIER LEADERS

Countries including the **United States, the Netherlands, and Israel** have been at the forefront of developing technological domains. Many Frontier Leaders are likely at or close to early-stage domain frontiers, where adoption of tools such as transgenic varieties and chemical inputs have reached near-full saturation.

Frontier Leaders tend to be on the cutting edge of innovation. However, they may be at risk of stagnating TFP growth due to diminishing returns from mature technologies, constrained adoption, or under-investment in public R&D.

Priority Investments

- Pushing out technological frontiers through sufficient public R&D investment.
- Gathering intelligence on potential domains for the next frontier.
- Strengthen agricultural and knowledge innovation.

FAST FOLLOWERS

India, Brazil, China, Vietnam, and other countries with robust TFP growth, have achieved strong productivity growth during the past two decades by rapidly adopting productivity-enhancing tools, thus progressing simultaneously across multiple domains.

A strong enabling environment—such as investment in public and private R&D, improved input market access, rural infrastructure development, and institutional reforms—have facilitated robust TFP growth.

Priority Investments

- Innovate agriculture and knowledge innovation systems to maintain adoption momentum. For example, prioritize robust public-private extension models.
- Strengthen human capital.
- Develop public-private partnerships.

POTENTIAL LEAPFROGGERS

Countries with sufficient political will, technical capacity, and favorable enabling conditions have the opportunity to leapfrog across paradigms by adopting innovations and approaches from later-stage paradigms.

Countries such as **Rwanda or Costa Rica**, or others in Southeast Asia, could bypass some of the costs of the transitional inefficiencies seen in other regions by investing strategically in digital agriculture, climate-smart technologies, and integrated systems approaches.

Priority Investments

- Identify high-impact entry points where later-stage tools can be deployed.
- Establish robust regulatory and intellectual property frameworks.
- Create flexible financing mechanisms.
- Adapt technologies to local context.

DEVELOPING ADOPTERS

Much of sub-Saharan Africa, as well as other low-income countries, still operate within early-stage paradigms, with significant untapped potential for productivity growth.

These countries face persistent adoption gaps due to weak infrastructure, underdeveloped input and output markets, institutional fragmentation, and socio-economic barriers that limit access to innovation. As a result, they have yet to benefit fully from later-stage domains' productivity-enhancing tools.

Priority Investments

- Strengthen agriculture and knowledge innovation systems, prioritizing farmer-led innovation, public and private extension systems, and bundled solutions.
- Adapt tools to local contexts.
- Establish regulatory harmonization.
- Stabilize financial instruments to sustain adoption as incomes fluctuate.



INPUT INTENSIFICATION

From Struggle to Strength: Turning Eroded Soils into a Thriving Farm International Fertilizer Development Center (IFDC)

In Uganda's Nyabyumba village, Sarah Tushabomwe and Denis Mwegisire transformed their struggling farm through the BRIGHT program, led by IFDC with support from the Netherlands' Ministry of Foreign Affairs. Using the program's Participatory Integrated Planning approach, they adopted soil and water conservation practices, improved seed and pest management, and diversified their crops. Yields and income rose significantly, enabling investments in nutrition, livestock, and education. Through the Nyabyumba Farmers Cooperative, they accessed inputs on credit and secured better market prices. With renewed confidence and a thriving farm, Sarah and Denis are steadily turning their vision for a resilient future into reality.

Photo: IFDC

EFFICIENCY OPTIMIZATION

Release and Commercialization of Iron Pearl Millet in One Year HarvestPlus

In Nigeria, the journey from crop variety release to commercialization typically takes at least three to four years to build seed systems. This slow process particularly hinders the adoption of higher-performing and nutritious crop varieties. However, the successful release and commercialization of the first iron pearl millet variety was achieved in just one year through the HarvestPlus Accelerated Release and Commercialization model. HarvestPlus successfully streamlined seed system bottlenecks, enabled pre-release seed bulking, and catalyzed private sector investment for this release. Through strategic partnerships and a special varietal release, iron pearl millet rapidly reached farmers and processors, addressing both malnutrition and climate resilience. This success story demonstrates how systemic efficiency and market alignment can fast-track biofortified crop adoption, offering a scalable model for transforming food systems in Nigeria and beyond.



Photo: HarvestPlus



SYSTEMS INTEGRATION

Increasing Productivity Through Intercropping and Agroforestry in Mexico

Heifer International

Since 2021, Heifer International has implemented Milpa for Life, a six-year initiative to strengthen the Mayan milpa system in Yucatán and Campeche, Mexico. The FAO recognizes the Mayan milpa as a globally important agricultural heritage system. It is a traditional intercropping and agroforestry model that integrates maize, beans, squash, and other crops with ancestral knowledge.

The project aims to double native maize yields, increase household income, and promote soil regeneration. By combining regenerative agriculture, inclusive markets, and animal husbandry (bees, poultry, and native pigs), Milpa for Life protects biodiversity, preserves cultural heritage, and fosters rural development, thus rooting productivity growth in sustainability.

Photo: Heifer International

The U.S. has long been a global Frontier Leader in productivity-driven agricultural growth. Between 1948 and 2021, agricultural output nearly tripled, fueled primarily by gains in TFP. However, this growth has been uneven, marked by cycles of rapid expansion, slowdown, and, most recently, stagnation. According to the National Accounts, peak TFP growth averaged 2.1 percent annually in the 1980s, but fell to just 0.28 percent per year between 2014 and 2023 (Figure 8; USDA, 2025). During the past decade, output growth has increasingly relied on input intensification rather than efficiency improvements, highlighting the diminishing returns of existing technologies, practices, and management strategies.

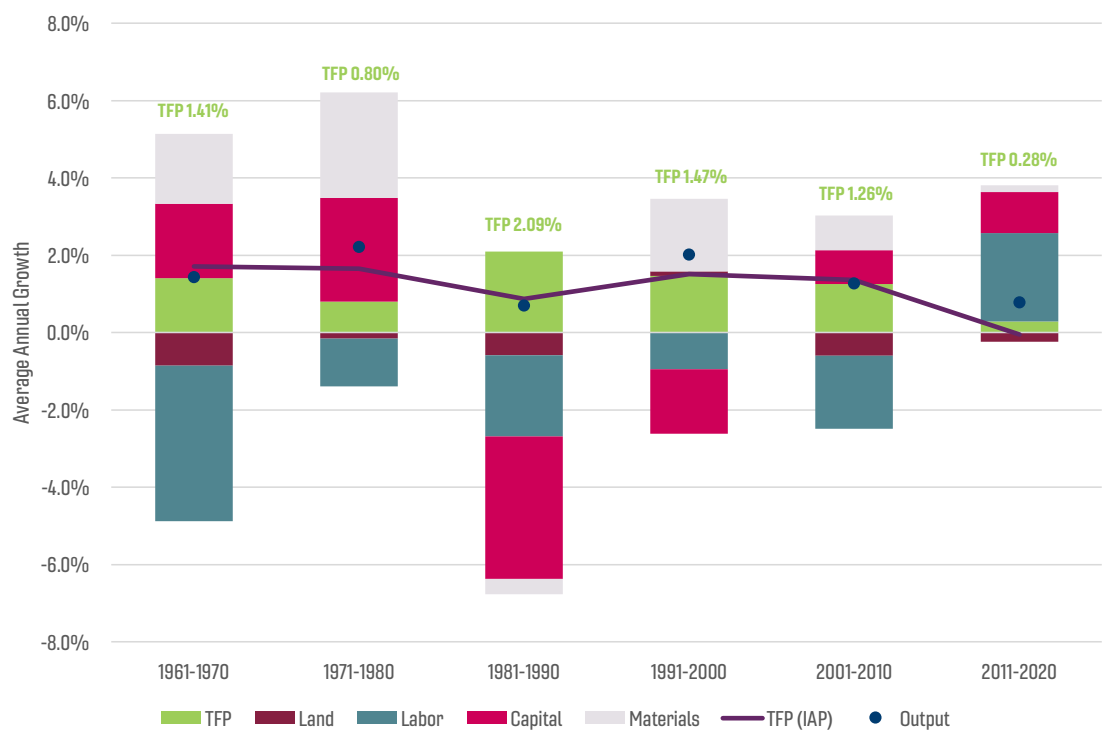
The consequences of this productivity plateau are far-reaching. Sluggish growth undermines U.S. competitiveness in the \$1.5 trillion global agricultural trade market, squeezes farm profitability as input costs outpace efficiency gains, and pressures rural livelihoods (FAO, 2022). Globally, slower U.S. productivity growth can lead to higher food prices and increase vulnerability to supply shocks in net-importing countries, affecting both American economic interests and international food security (Fuglie et al., 2021). Slower productivity growth also undermines sector sustainability, as greater reliance on input intensification can accelerate soil degradation, nutrient runoff, and greenhouse gas

emissions (Fuglie et al., 2024; Kopittke et al., 2019). These complex dynamics can be clearly understood using the TFP Growth Frontier model, which can identify where productivity progress has slowed, diagnose the underlying constraints, and chart new pathways to push the frontier outward.

U.S. PRODUCTIVITY GROWTH TRENDS AND DRIVERS

Two complementary datasets provide insights into U.S. agricultural productivity growth trends. The USDA National Agricultural Productivity Accounts uses U.S.-specific prices and a detailed set of domestic input-output data, generating a finely tuned measure of on-farm technical change and resource use efficiency (USDA, 2025). In contrast, the International Agricultural Productivity (IAP) methodology harmonizes data across countries, applying a common global price framework and purchasing power parity adjustments, making it possible to benchmark U.S. performance within a global context (Fuglie, 2025; USDA ERS, 2025). Figure 8 illustrates the sources of U.S. agricultural output growth from the National Accounts and compares them with the TFP growth rates from the IAP dataset (purple line), revealing how productivity has evolved within the United States and how U.S. productivity growth compares to global trends.

Figure 8. U.S. Sources of Agricultural Output Growth – National Accounts with IAP TFP Growth Rate, 1961-2020



Note: U.S. National Accounts data are represented in the stacked bars (USDA, 2025) and the IAP TFP Growth rate is denoted by the purple line (Fuglie, 2025).

U.S. PRODUCTIVITY GROWTH TRENDS AND DRIVERS BY DECADE

1960s.

Beginning in the 1960s, TFP growth emerged as the primary driver of agricultural output (Wang et al., 2015a). The increasing adoption of new high-yield genetics, synthetic fertilizers, effective pesticides, and other improved inputs delivered exceptional output gains with relatively little additional input use—demonstrating the capacity of TFP growth to generate more value from the same or fewer resources (Wang et al., 2015a). During this period, the use of labor and land declined, while reliance on intermediate goods and capital rose to sustain the more productive farming systems (Wang et al., 2018). This transition from extensification and input-driven growth to efficiency-based gains laid the groundwork for continued productivity improvements in the decades that followed.

1970s.

The 1970s saw a marked slowdown in productivity growth, averaging just 0.8 percent annually, as broader economic conditions reshaped farming incentives. Domestic and global pressures reinforced a “go big or get out” mindset in U.S. agriculture. High commodity prices—driven by reduced U.S. grain reserves and poor weather abroad—spurred demand for American farm products. Farmers responded by expanding production, investing heavily in intermediate inputs, machinery, and other capital assets, which was supported by lenders eager to provide credit (Wang et al., 2015b). This era of input intensification, shaped by economic signals and policy, temporarily overshadowed TFP as the leading source of growth. By the end of the decade, however, the Federal Reserve raised interest rates to curb inflation, and an embargo on grain shipments to the Soviet Union further disrupted markets. Together, these shocks set the stage for the farm crisis that would fundamentally reshape rural America (Iowa PBS, 2013).²

1980s.

The 1980s stand out as a paradox in U.S. agricultural history—even as the sector endured its most severe economic downturn since the Great Depression, it achieved its highest TFP growth rate to date, averaging more than 2 percent annually. The “Farm Crisis”—driven by a global recession, a soaring U.S. dollar, and restrictive domestic monetary policies that pushed real interest rates near 16 percent—devastated farm incomes, farmland values, and credit access, sharply reducing capital investment (Wang et al., 2015b). With input use contracting—particularly for capital—farmers were forced to operate far more efficiently, fully utilizing the productivity tools developed during the Input Intensification era. TFP growth became a lifeline, enabling the sector to adapt and redirect resources toward more productive managers and operations (Wang et al., 2015b).³

² While the IAP dataset suggests strong TFP growth in the 1970s, the methodology masks the productivity impact of high input prices captured by the National Accounts.

³ The IAP TFP growth rate for the 1980s is lower, at 0.87%, as its input accounting technique will not fully capture the productivity improvements derived from maturing Input Intensification tool adoption.

1990s.

TFP growth cooled in the 1990s to an average of 1.4 percent per year, yet it remained the primary source of agricultural output growth as the sector rebounded with renewed investment in capital and intermediate goods. Much of this growth stemmed from the commercialization and adoption of new technologies, particularly in biotechnology. The introduction of genetically modified (GMO) crops in 1996—with traits such as insect resistance and herbicide tolerance—reduced the use of tillage and certain pesticides, cut input costs, improved soil health, and increased farm profitability (FDA, 2024). Expanded private-sector R&D investment, building on momentum from the 1980s, played a central role in driving these advances (Wang et al., 2015b). The decade also marked the early adoption of precision agriculture tools, such as GPS guidance systems, which further enhanced efficiency and reduced waste (Schimmelpfennig, 2016).⁴

2000s.

TFP growth continued to decelerate in the 2000s, reflecting a broader trend observed across the U.S. economy (Cardarelli & Lusinyan, 2015). Stagnation in agricultural productivity growth can be attributed to the policy and investment patterns of earlier decades. The benefits of public agricultural R&D investments have a significant time lag, with the largest effects on TFP often appearing up to 30 years after initial spending (Ortiz-Bobea et al., 2025). Public R&D funding growth, which had expanded rapidly through the mid-20th century, began to slow in the early 1980s and plateaued around 2000 (Pardey & Alston, 2020). The deceleration of TFP growth during this decade, therefore, reflects diminishing returns from a public “knowledge stock” built from past investments (Ortiz-Bobea et al., 2025).

2010s.

TFP growth in U.S. agriculture slowed sharply in the 2010s, reaching a historical minimum of 0.28 percent annually. First, the long lag between research and investment and measurable productivity gains means the effects of reduced public R&D are only beginning to appear (Wang et al., 2018). Second, while new digital and precision technologies—such as variable-rate applications (VRT) and yield monitors—emerged, adoption was uneven. GPS guidance systems were widely implemented, for example, while more complex tools such as VRT and soil mapping lagged, with adoption below 25 percent for planned acreage of winter wheat, cotton, sorghum, and rice (McFadden et al., 2023). This “valley of death” between innovation and on-farm practice reveals the need for strong knowledge transfer, extension services, and adoption support to convert new technologies into broad productivity gains (Agnew & Nakelse, 2024).⁵

Although the IAP dataset does not capture the nuance of domestic productivity growth trends, it reveals that the U.S., once a global leader in agricultural productivity, is now experiencing slower TFP growth compared to Fast Followers such as China and countries in South Asia that have made robust progress in productivity gains. The U.S. has already captured much of the low-hanging fruit from early-stage technological domains and must now focus on frontier-pushing investments or adopting tools from the Efficiency Optimization and Systems Integration domains.

⁴ The IAP TFP growth rate is similar during this decade, suggesting that there were no major input price shocks or rapid technological transitions.

⁵ The -0.05 IAP growth rate (Figure 8) suggests that global input volatility is affecting productivity. Given the methodology's quality-adjusted land measures, negative growth also signals the impact of climate stress on agricultural productivity.

DIAGNOSING PLATEAUS, DRIVING PROGRESS: INSIGHTS FROM THE TFP GROWTH FRONTIER

The U.S. agricultural sector stands at a critical inflection point. From pioneering hybrid crops and transgenic varieties to scaling digital agriculture and precision technologies, the U.S. has been a Frontier Leader—expanding its own productivity base while contributing to the universal TFP Growth Frontier through scientific excellence, private sector innovation, technology transfer, and global knowledge diffusion. Yet, despite this innovation track record, growth has slowed. The TFP Growth Frontier model highlights four underlying causes of this productivity plateau and what can be done to address them.

DIMINISHING RETURNS FROM EARLY-STAGE DOMAIN TOOLS

Productivity-enhancing tools from the Input Intensification domain—including hybrid crops, selective breeding, mechanization, crop protection, and fertilizers—drove strong gains in U.S. agricultural TFP during the 1980s and 1990s. However, these tools are now delivering diminishing efficiency gains, creating a plateau in productivity growth.

Genetically modified (GM) crops clearly illustrate this phenomenon. Early-stage single-trait varieties, such as insect-resistant (Bt) maize, not only increased yields by about 25% compared with conventional varieties but also reduced the need for certain insecticides (Klümper & Qaim, 2014; National Academies of Sciences, Engineering, and Medicine et al., 2016). Herbicide-tolerant crops allowed farmers to use broad-spectrum herbicides, reducing mechanical tillage, saving labor and fuel, and decreasing erosion (Brewster, 2018; Qaim,

2010). These early-stage traits demonstrate the large productivity gains possible when novel tools target key biological constraints; however, productivity growth from these traits has largely been exhausted. In contrast, later-stage GM traits—including stacked traits, drought tolerance, and biofortification—focus on more complex challenges, such as sustaining production in the face of environmental stressors, combating mounting pest and weed pressures, and enhancing the nutritional value of crops (Berkowitz, 2017; Effland et al., 2022; Qaim, 2010). While these traits provide incremental yield improvements, ensure farming in stressed environments, and provide consumer-facing benefits, they generally provide only modest productivity gains.

Input Intensification domain tools also are reaching biological limits. In livestock, feed conversion ratios in poultry and swine are approaching physiological ceilings, while productivity gains in dairy from selective breeding have decelerated. In crops, photosynthetic efficiency in C_3 cereals, such as wheat, has reached roughly 2.4 percent of solar energy capture—already more than half of the theoretical maximum (X.-G. Zhu et al., 2008). Environmental pressures further compound these diminishing returns. Soil degradation and aquifer depletion reduce local yields and limit irrigation potential, while heat stress and climate variability impose additional constraints on production (Elliott et al., 2014; Lopez et al., 2022; Thaler et al., 2021). Across crops, livestock, aquaculture, and horticulture, the natural environment has shifted from a passive backdrop to an active constraint. Reproducing the productivity dividends of prior decades will require substantial public R&D investment and the application of new scientific knowledge and methods to push out the Input Intensification domain frontier.



Photo: Farm Foundation

DRIVING ADOPTION

Showing How a Systems Approach to Regenerative Agriculture Can Improve Productivity, Increase Diversification, and Reduce Inputs
Farm Foundation

Farm Foundation recently opened an Innovation and Education Campus north of Chicago on a farm that was in production from the mid-1860s until the early 2000s. The homestead had sat fallow for many years, allowing for weeds and invasive species to take over what was once productive farmland. Driven by their mission to build trust and understanding at the intersection of agriculture and society, the Farm Foundation rolled out a strategy to rebuild the soil by demonstrating ten regenerative soil health practices and a wide range of new technological innovations. Practices like planning perennial crops, keeping the soil under cover crops at all times, and limiting tillage are necessary to rebuild productivity and improve the overall health of the farm.

LIMITED ADOPTION OF LATER STAGE DOMAIN TOOLS

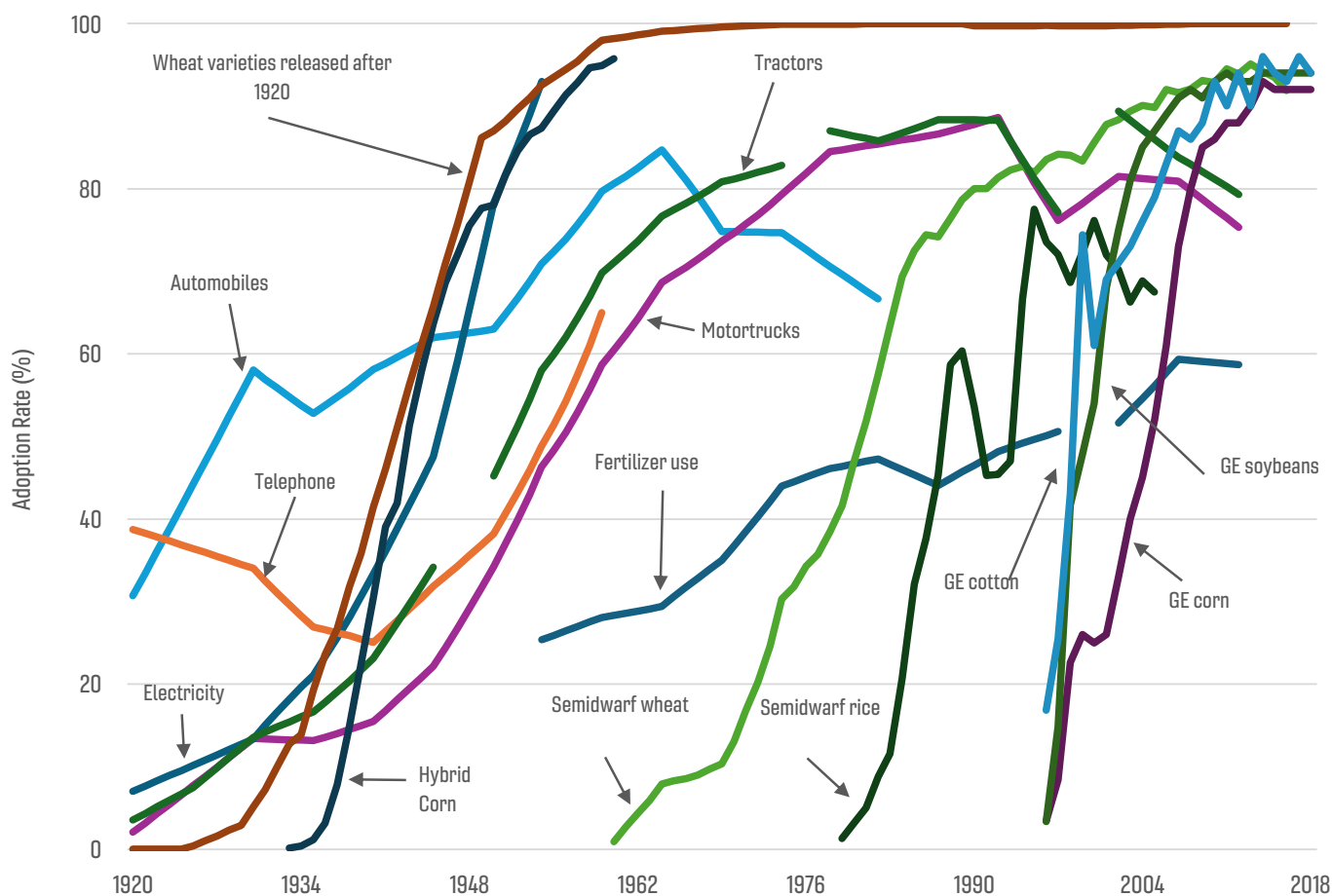
Adoption patterns of proven productivity-enhancing tools shape the trajectory of TFP growth (Pardey & Alston, 2020). The lagging growth of the past decade reflects two contrasting trends: the near-saturation adoption of early-stage domain tools and uneven, lagging uptake of later-stage technologies.

Technologies from the Extensification and Input Intensification domains—such as automobiles, tractors, synthetic fertilizers, hybrid crops, and semi-dwarf wheat and rice—have diffused almost universally across U.S. farms (Figure 9). These early-stage tools generated substantial productivity gains during the mid-20th century, transforming labor efficiency, crop yields, and farm profitability. However, with adoption rates near 100 percent for decades, the marginal gains from these technologies are now largely exhausted as farms operate at or near the efficiency ceilings these tools can deliver (Pardey & Alston, 2020).

By contrast, Efficiency Optimization and Systems Integration domain tools—such as variable-rate applications, GPS-enabled yield monitors, digital management platforms, guidance auto-steering, satellite and drone imagery, and advanced automation systems—remain unevenly adopted (Figure 10).

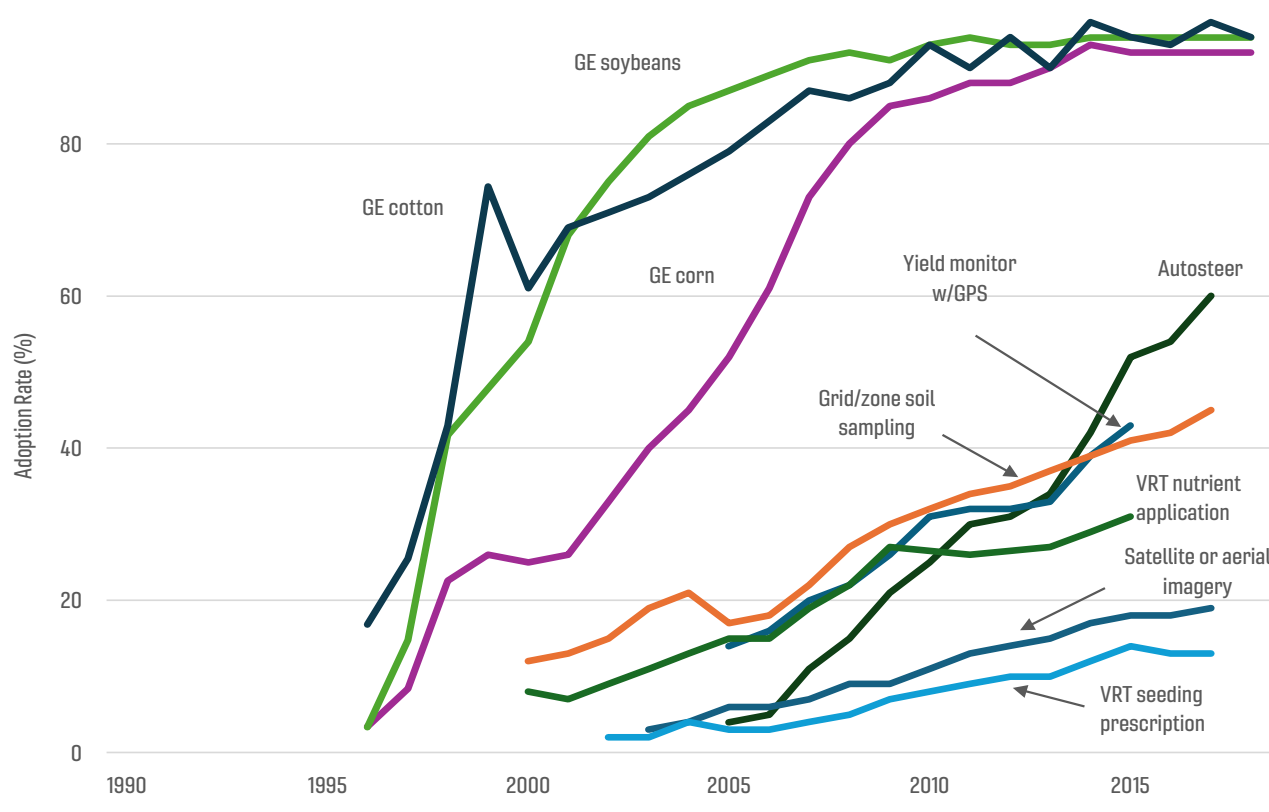
In row crops, slow uptake of site-specific nutrient management and drone-based monitoring limits progress in yield optimization and resource efficiency. Although guidance auto-steering is now common among large operations, variable-rate nutrient application systems are used on only 37 percent of corn acreage, and drone-based sensing remains below 10 percent (McFadden et al., 2023; McFadden & Lim, 2024). Livestock systems show similar gaps: precision feeding, automated health monitoring, and sensor-driven environmental controls are still underutilized, slowing gains in feed conversion and animal welfare. In aquaculture, adoption of disease management, feed optimization, and environmental monitoring tools

Figure 9. Adoption of Early-Stage Domain Tools



Source: Pardey & Alston, 2020.

Figure 10. Adoption of Later-Stage Domain Tools



Source: Pardey & Alston, 2020.

remains low, constraining both productivity and sustainability (Knapp & Rubino, 2016; Naylor et al., 2009). Horticulture technology adoption is highly uneven as well, with greenhouse automation and environmental control technologies concentrated in large, vertically integrated operations, leaving smaller producers below the Efficiency Optimization domain frontier.

Adoption disparities by farm size and geography are stark. Large farms report auto-steering adoption rates above 70 percent, compared to 52 percent on midsize farms and single-digit rates among small family farms (McFadden, 2023; McFadden & Lim, 2024). Geographically, Midwestern states such as North Dakota and Nebraska report adoption rates over 50 percent, while eastern states such as West Virginia remain below 10 percent (McFadden, 2023). These gaps exacerbate differences in profitability, efficiency, and competitiveness across the sector.

Near-saturation of early-stage tools and uneven, lagging adoption of advanced later-stage technologies are major contributors to stagnating productivity. Unlocking the next frontier of agricultural efficiency will require targeted efforts to reduce adoption barriers—through improved access to knowledge, capital, and infrastructure—to fully realize the potential of advanced tools.

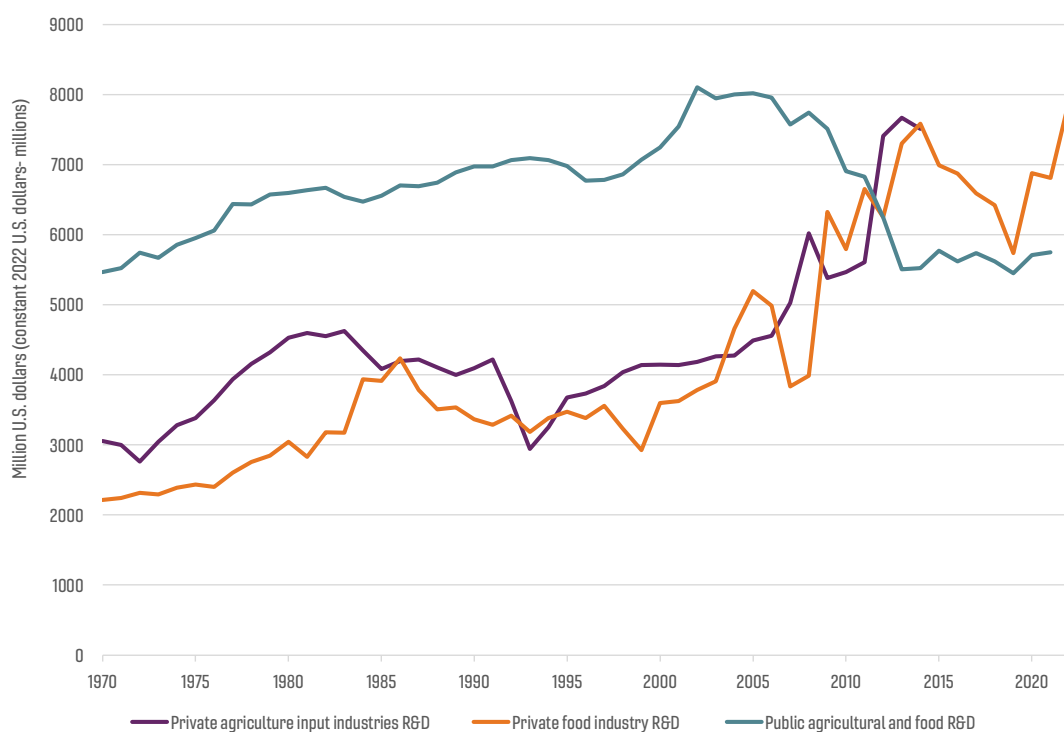
For more details on strategies to target adoption barriers, see the 2023 and 2024 GAP Reports.

FRICIONS THAT LIMIT THE EXPANSION OF EXISTING DOMAIN FRONTIERS

Expanding domain frontier productivity ceilings—particularly the still-emerging Efficiency Optimization and Systems Integration frontiers—is increasingly constrained by declining public R&D investment and fragmented institutional coordination. U.S. Government spending on agricultural R&D fell by nearly 30 percent, from \$8.1 billion in 2002 to \$5.7 billion in 2021 (Figure 11). Because returns on research often take decades to materialize, today's slowdown in U.S. TFP growth reflects the cumulative effects of long-term underinvestment (Pardey et al., 2016). This challenge is further compounded by coordination inefficiencies between federal agencies, land-grant universities, and State Agricultural Experiment Stations. Although collaborations are active, there is room to strengthen the cross-disciplinary and multi-sectoral relationships needed to address complex productivity challenges.

The private sector emerged as the largest driver of U.S. agricultural R&D in 2012 (Figure 11). By 2022, private-sector R&D reached record levels (Figure

Figure 11. Public and private investments in agri-food research, 1970-2022



Source: Nelson, 2025.

Note: Due to recent shifts in industry structure and the rise of new industries and technologies, private investment estimates beyond 2014 are not yet available.

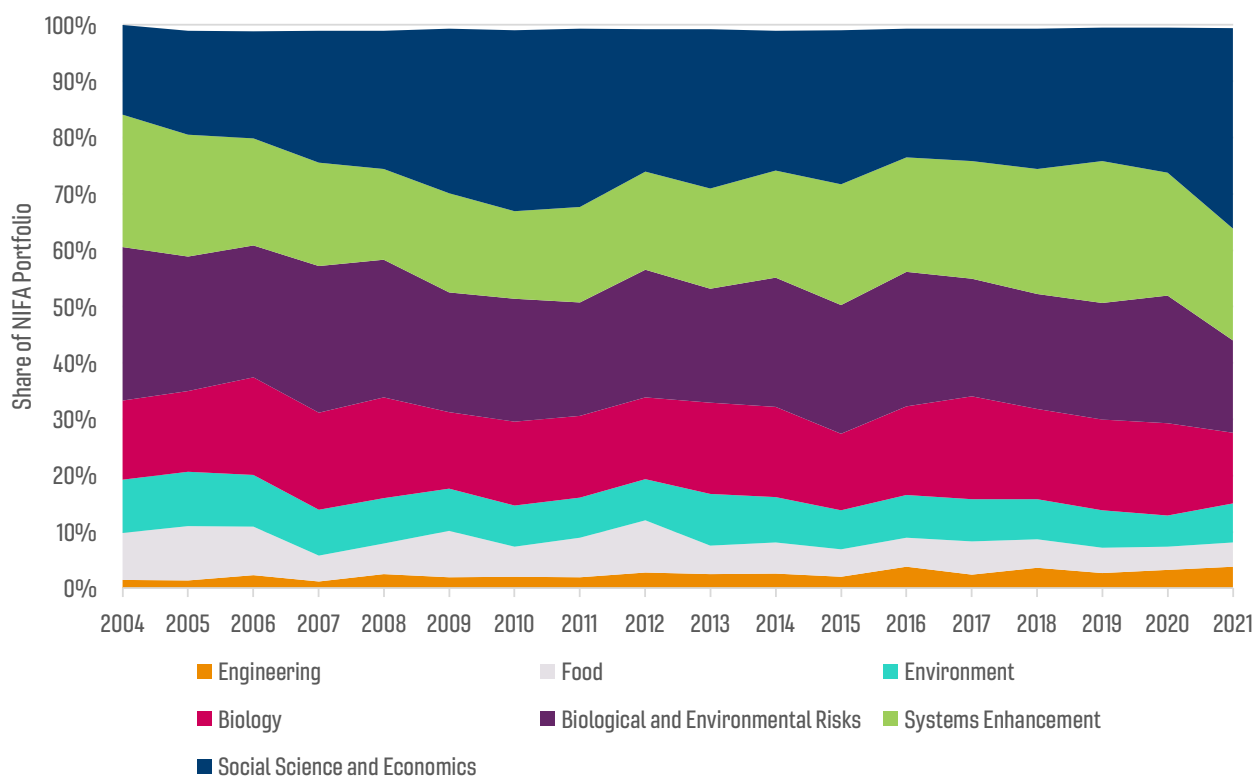
11) but remains concentrated in a few major crops. Corn, soybeans, and cotton dominate U.S. breeding pipelines, with corn alone representing 51 percent of the seed market (Deconinck, 2020). In 2021, the seven largest seed firms reinvested more than \$6.5 billion—about 10 percent of sales—into crop improvement (Fuglie, 2023), generating significant advances in seed technologies and efficiency. Stronger public-private collaboration could contribute to broad-based TFP growth, particularly in areas critical for long-term productivity that attract less private investment (Heisey & Fuglie, 2018).

In addition to reduced overall spending, federal research priorities have shifted away from core productivity-enhancing science. For example, although USDA's National Institute for Food and Agriculture (NIFA) budget doubled between 2004 and 2021, the composition of its research portfolio has changed sharply since 2004 (Figure 12). The NIFA funding portfolio is grouped into seven categories, shown in Figure 12 (USDA NIFA, 2025). Four of these categories—engineering, biological and environmental risks, biology, and systems enhancement—contribute directly to productivity growth, while the remaining categories address other key aspects of food and environmental systems. By 2021, social science and economics—covering farm and market economics, trade and

policy analysis, consumer behavior, and rural development—had grown by 126 percent, accounting for 35.7 percent of total funding, becoming the largest share of the portfolio.

By contrast, funding for foundational science critical to long-term productivity growth has eroded. Systems enhancement related topics, which support soil-water-nutrient management, crop and animal management systems, integrated pest management, and agroforestry, represented 19 percent of funding—a 16 percent decline since 2004. Support for biological and environmental risk research—encompassing pest and disease pressures in plants and animals, food safety, and disaster preparedness—has fallen by 65 percent, down to just 16 percent of the portfolio by 2021. Biology, including genomics, genetic improvement, plant physiology, and reproductive science, declined to 12 percent, a 10 percent drop since 2004, despite being essential for driving future productivity breakthroughs. Engineering, which underpins the Efficiency Optimization domain through innovations in systems design, irrigation, automation, and precision technologies, accounts for only 3 percent of NIFA funding. Although this represents a 155 percent increase since 2004, the share remains far below what is needed to push out the Efficiency Optimization domain frontier.

Figure 12. U.S. National Institute of Food and Agriculture Funding Portfolio by Theme, 2004-2021



Source: USDA NIFA, 2025.

Meanwhile, environmental research (e.g., soil and water management, biodiversity conservation, pollution mitigation, and environmental economics) and food research (e.g., processing technologies, product development, and quality systems) continue to represent relatively small portions of the portfolio, at 7 percent and 4 percent, respectively.

This shift signals an urgent need to rebalance federal agricultural research priorities. Without stronger and sustained support for foundational biology, engineering, and productivity-focused research, the U.S. risks eroding the scientific base necessary to drive the next generation of innovation and sustained productivity growth.

The fragmentation and complexity of the U.S. regulatory environment also constrain advancements in domain frontiers by raising innovation costs and lengthening time-to-market. For example, launching a new crop-protection active ingredient averages about US\$301 million and approximately 12 years (AgBio Investor, 2024). Developing a biotech trait costs about US\$115 million, with approximately 38 percent of costs and 51 percent of development time tied to regulatory compliance (AgBio Investor, 2022). Multi-agency oversight under the Coordinated Framework for the Regulation of Biotechnology further amplifies these costs; USDA estimates that eliminating duplicative reviews would save developers US\$1.6-5.6 million

per genetically engineered plant (USDA APHIS, 2019). These regulatory hurdles slow the pace of technological progress, constraining the ability to push productivity frontiers outward and delaying the adoption of innovations that could drive productivity growth.

BARRIERS THAT IMPEDE TRANSITION TO THE NEXT DOMAIN

The U.S. transition toward the Systems Integration domain largely remains stuck at the pilot stage. Despite their promise, innovations such as integrated crop-livestock systems, circular nutrient flows, and ecosystem service markets face high barriers. Without standardized MRV protocols and affordable tools, implementation costs balloon, and confidence in performance metrics and outcomes (e.g., soil health) remains low. At the farm level, unresolved trade-offs between yields, biodiversity, and emissions further complicate adoption. Ecosystem-service payments seldom offset production trade-offs, and fragmented governance across the USDA, the Environmental Protection Agency (EPA), states, and supply chains further slows progress. As a result, the System Integration domain's benefits remain largely theoretical or confined to small-scale trials.

Several structural headwinds are slowing the emergence of this domain:



DRIVING ADOPTION

Building U.S. policy to achieve optimum agricultural productivity

The National Association of the State Departments of Agriculture (NASDA)

Policy alignment is essential to accelerating sustainable agricultural productivity growth. Through strategic coalitions, NASDA—a nonpartisan, nonprofit association representing the elected and non-elected officials of the state departments of agriculture—has strengthened policy recommendations for Congress and federal agencies. NASDA's collaborative approach of uniting voices has also resulted in concrete outcomes, including increased funding for Farm Bill programs like the Market Access Program, getting the Ocean Shipping Reform Act signed into law, and creating joint initiatives on PFAS with the U.S. EPA and the Environmental Council of the States. Together, NASDA's network achieves one shared goal through systems innovation: a thriving, resilient, and sustainable agricultural future.

Photo: NASDA

- 1. Underinvestment in convergent research and innovation.** The National Academies have called for a new generation of research that integrates life sciences, engineering, computation, and systems thinking to deliver step-change productivity growth (National Academies of Sciences, Engineering, and Medicine, 2022). Yet, funding for this type of interdisciplinary science remains thin, limiting the development of tools and models needed to manage complex, multi-layered systems.
 - 2. Digital infrastructure and data interoperability face challenges.** Systems Integration depends on multi-source data to operate effectively and demonstrate outcomes; yet persistent barriers—including uncertainty around return on investment, workforce skill gaps, data privacy and security concerns, interoperability, and the absence of common data standards—hinder progress on establishing effective data infrastructure (GAO, 2024).
 - 3. Natural resource constraints are also tightening integration margins.** Water scarcity and long-term groundwater depletion in key irrigated regions, such as the High Plains/Ogallala Aquifer (McGuire & Strauch, 2024), complicate the economics of stacking multiple practices where irrigation is essential to productivity.
 - 4. Organizational and demographic barriers limit the speed of adoption.** The Cooperative Extension System, critical for diffusing new knowledge and practices, faces resource and staffing pressures as its responsibilities expand while funding remains flat (Bickell, 2024). Demographic realities further constrain uptake: the average U.S. producer is now 58.1 years old, and nearly 39 percent of farmland is rented (Callahan, 2025; USDA NASS, 2022). Shorter planning horizons on rented ground dampen producers' willingness to commit to multi-year, system-based investments.
 - 5. Immature market incentives hinder momentum.** Ecosystem-service and carbon markets have the potential to support integrated systems, but USDA assessments show that high transaction and MRV costs, combined with limited and uncertain returns, keep participation low and investment shallow (USDA, 2023).
- Collectively, these frictions raise the cost of developing the Systems Integration domain. Without clearer and faster regulatory pathways, truly interoperable digital infrastructure, stronger investment in convergent R&D and extension, and market mechanisms that reward systems-level performance, the transition to Systems Integration will remain incremental, and its potential to drive productivity growth will remain unrealized.



Photo: CAST

EFFICIENCY OPTIMIZATION

AI in Agriculture: Opportunities, Challenges, and Recommendations
Council for Agricultural Science and Technology (CAST)

This paper, authored by CAST in 2025, explores how AI is revolutionizing agriculture through technologies that integrate across entire systems—from decision-support platforms like ExtensionBot to predictive tools in livestock, genetics, food safety, and robotics. These innovations enable smarter, more efficient production but face challenges like data incompatibility, connectivity gaps, and a lack of workforce training. CAST calls for bold investment, standards development, and inclusive policies to ensure AI benefits farms of all sizes. AI represents a system-level shift in agricultural productivity—poised not just to optimize, but to redefine how agriculture operates in the 21st century.

RECOMMENDATIONS FOR REINVIGORATING U.S. TFP GROWTH

The productivity slowdown has serious implications for the U.S. agricultural sector and beyond. It threatens to erode the nation's global competitiveness and impede progress on global food and nutrition security, while driving greater reliance on environmentally unsustainable practices. It also risks widening the socioeconomic divide between large, technologically advanced farms and smaller, resource-constrained operations. Reversing this trend demands a multi-pronged strategy to realign research and policy investments, innovation and knowledge systems, and adoption drivers to push out the TFP Growth Frontier.

REIGNITE PUBLIC R&D INVESTMENT

Public R&D spending is the cornerstone of sustainable productivity growth; decades of underinvestment have slowed the pace of discovery. Evidence suggests that pushing out the TFP Growth Frontier will require increasing public agricultural R&D investment by \$2.2 billion, comparable to the post-World War II expansion of the U.S. research enterprise (Pardey et al., 2016).

KEY ACTIONS INCLUDE:

- **Funding:** Expand NIFA and other funding streams for productivity-enhancing and convergent research to support complex, systems-level innovation without compromising the pre-commercial scientific discovery needed to achieve productivity gains. Research funding in technologies, such as gene-editing and AI/machine learning, that will push out existing domain frontiers is also critical.

- **Collaboration:** Incentivize collaborative research networks that bridge land-grant universities, federal labs, and private industry, ensuring rapid translation of foundational science into field-ready solutions.

CLOSE THE ADOPTION CHASM

Accelerating the adoption of productivity-enhancing technologies, practices, and management tactics across all scales of production is essential to reaching the TFP Growth Frontier. Closing the gap between innovation and adoption requires a revitalized agricultural knowledge and innovation system (AKIS) with coordinated support across financial, infrastructure, and human capital dimensions.

KEY ACTIONS INCLUDE:

- **Financial:** Provide targeted cost-share programs, adaptive crop insurance products, and low-interest technology adoption loans to support small and mid-sized farms in managing upfront capital costs.
- **ICT Infrastructure:** Invest in high-speed rural broadband and precision agriculture connectivity to support real-time data collection, analysis, and decision-making in the field.
- **Interoperability:** Fund and incentivize the development and adoption of industry-wide data and equipment standards, enabling compatibility across platforms and reducing switching costs for producers.

SYSTEMS INTEGRATION

Advanced Technologies for Monitoring Livestock Behavior and Health

Purdue University

The "One Health" approach emphasizes the link between animal, human, and environmental health. At Purdue's Department of Animal Sciences, researchers are developing automated technologies to detect livestock illness through subtle behavioral changes before symptoms appear. Computer vision with pen cameras monitors ear posture, facial expression, and social isolation in dairy calves. These tools can detect illness early, support farmer decision-making, and prevent disease spread, improving livestock health, welfare, and biosecurity. By enabling earlier intervention, they may reduce treatment costs, minimize production losses, enhance productivity, protect human health, and reduce antibiotic use in livestock operations.

Research by: Heather W. Neave and Gary R. Burniske



Photo: Purdue University

- **Human Capital:** Expand investment in the cooperative extension system's human resources by increasing staffing, modernizing training, and embedding digital agriculture specialists to support data-driven decision-making and trust-building with producers.

STRENGTHEN THE REGULATORY ENVIRONMENT

A modern, efficient, and science-based regulatory framework is critical to reducing innovation bottlenecks and ensuring the timely deployment of productivity-enhancing technologies. For example, the current Coordinated Framework for Biotechnology, established in 1987, has not kept pace with scientific advancements, resulting in prolonged and costly approval processes for genetically engineered traits and crop-protection technologies.

KEY ACTIONS INCLUDE:

- **Coordination:** Streamline multi-agency oversight to eliminate duplicative reviews, reducing both approval timelines and compliance costs.
- **Enabling Environment:** Develop clear, predictable regulatory pathways for emerging technologies such as gene editing, biological crop inputs, and AI-driven farm management systems.
- **Evidence-based Decision making:** Embedding outcome-based risk assessment frameworks that balance safety and innovation, enabling faster and more targeted deployment of new tools.



EFFICIENCY OPTIMIZATION

Driving Innovation with DAWN Agricultural Decision-Making Tool *Daugherty Water for Food Global Institute at the University of Nebraska*

The Dashboard for Agricultural Water and Nutrient Management (DAWN) is a free, web-based decision-support tool developed to help Corn Belt producers optimize water and nutrient inputs for efficiency gains. Supported by USDA-NIFA and developed by a team of researchers, including those at the Daugherty Water for Food Global Institute at the University of Nebraska, the tool translates complex climate data into six-month forecasts that can be applied for real-time, region-specific, actionable insights. With over 400 users, DAWN is gaining traction and attracting private-sector interest. By bridging science and practice, DAWN supports more efficient, resilient farming and highlights the importance of collaborative, farmer-informed innovation in digital agriculture.

Photo: Daugherty Water for Food Global Institute at the University of Nebraska

FOSTER PUBLIC-PRIVATE COLLABORATION

Bridge the “Valley of Death” between research and widespread adoption through close collaboration between public and private stakeholders. Public investment often seeds breakthroughs, while the private sector excels at scaling and deployment.

KEY ACTIONS INCLUDE:

- **Accelerate:** Leverage the State Agriculture Experiment Station infrastructure to pilot and refine emerging technologies in real-world conditions, shortening the research-to-practice pipeline.

- **Finance:** Mobilize financing mechanisms to support translational research, particularly in underserved regions and sectors where private returns may be lower but societal benefits are high.
- **Enabling Environment:** Create exemplars for data-sharing partnerships that create legal frameworks to protect privacy and intellectual property while enabling feedback loops and accelerated systems-level innovation.

By reinvesting in foundational science, accelerating adoption, modernizing regulation, and fostering stronger collaboration between the public and private sectors, the U.S. can re-establish itself as a Frontier Leader of the TFP Growth Frontier.



EFFICIENCY OPTIMIZATION

Expanding the Next Frontier with John Deere Precision Upgrades

John Deere

John Deere's Precision Upgrades strategy supports agricultural productivity growth by broadening access to technologies that enhance efficiency, productivity, and integration. These upgrades range from foundational tools that improve job quality across mixed fleets to advanced systems like electric meters, nozzle control, and See & Spray automation. By enabling retrofits for both Deere and non-Deere equipment—including solutions like SurePoint and SmartApply—farmers can transition from input intensification to system-level integration. This approach helps overcome barriers to technology adoption, fosters more sustainable production practices, and contributes to global efforts to revitalize total factor productivity in agriculture.

Photo: John Deere

The following five evidence-based policy, investment, and research priorities inform actionable steps to reinvigorate critically needed sustainable TFP growth. The priorities outlined here include illustrative actions to reach or expand the Input Intensification, Efficiency Optimization, and Systems Integration frontiers. Effective strategies will bundle interventions, policy, and investments across multiple priorities.

PRIORITY 1 – INVEST IN AGRICULTURAL KNOWLEDGE AND INNOVATION SYSTEMS

Fostering technological advancements, developing improved practices and management techniques, and adapting existing technologies to new contexts can expand the TFP Growth Frontier. This is equally important in regions with robust growth as well as regions where growth is lagging. Public and private R&D have demonstrated returns to productivity growth. For example, between 1962 and 2011, each 1 percent increase in R&D capital led to a global average 0.18 percent increase in TFP growth. Returns on TFP growth vary significantly across regions: high-income countries saw a 0.67 percent increase, compared to 0.38 percent in low- and

middle-income countries and just 0.17 percent in sub-Saharan Africa (Fuglie, 2018).

Too often, solutions from R&D get stuck on the shelf, never reaching the agri-food system actors—especially smallholder producers—who need them the most. Additionally, some existing knowledge, practices, and technologies have not yet reached last-mile farming communities. Market failures and socio-economic disparities limit the adoption of productivity-enhancing technologies.

Agriculture knowledge and innovation systems (AKIS) build critically needed dissemination and adoption pathways for a domain’s productivity-enhancing tools. This includes the infrastructure (social, political, physical), human capital and skills development, financial systems, partnerships, socio-cultural considerations, and environmental conditions required for producers at all scales of production to access and sustainably adopt productivity-enhancing tools across all technological domains. Investments beyond R&D are essential for achieving the target agricultural productivity growth rate.

POLICY	Priority 1 Actions INVESTMENT	RESEARCH
<p>Use next-gen data intelligence and machine learning to identify evidence-based, high-impact policy mechanisms that will expand domain frontiers and facilitate adoption.</p> <p>Learn more about the GAP IQ platform (see inside back cover).</p>	<p>Develop a differentiated, diversified portfolio across the four technological domains.</p> <p>Leverage infrastructure, e.g., the State Agricultural Experiment Stations or CGIAR, to shorten productivity-enhancing tools’ research-to-practice pipelines.</p>	<p>Establish new and strengthen existing international research consortia to advance Systems Integration—uniting universities, industry leaders, and venture investors to spin out frontier-pushing technologies with scalable spillovers.</p>

EFFICIENCY OPTIMIZATION

Data-Powered Discovery: Transforming Crop Protection with ‘Omics’
The Syngenta Group

Syngenta’s new molecular techniques significantly accelerate the development of crop protection products. Traditionally, the journey from molecule discovery to a market-ready product could take up to 12 years and cost hundreds of millions of dollars. By integrating ‘omics’ technologies—transcriptomics, metabolomics, cell painting, and proteomics—early in the development process, Syngenta can identify potential risks and optimize chemical structures much faster. This approach generates up to four million data points per molecule, allowing for quicker and more precise adjustments. Think of it like scouting a star athlete—rather than just knowing their height and weight, four million data points gives us their speed, strength, endurance, reaction time, and countless other metrics that together predict how they’ll perform in different situations. As a result, the time and cost of development are substantially reduced, ensuring safer products reach farmers more efficiently .



Photo: The Syngenta Group

DRIVING ADOPTION

Driving Productivity Through Markets and Collective Action: The Kyendagara Cooperative's Transformation in Uganda

Sasakawa Africa Association

In Uganda's Kitagwenda District, the Kyendagara Area Cooperative Enterprise (KACE) has transformed from a subsistence group into a thriving commercial hub with support from the Sasakawa Africa Association and Japan's Ministry of Foreign Affairs. Through the One Stop Centre Association model, KACE gained access to training, finance, inputs, and markets—enabling farmers to invest in productivity-enhancing practices and transition from subsistence to commercial-scale production. Certified processing and access to formal markets boosted maize sales and income, while collective bulking tripled volumes in one year. Membership more than doubled, and new jobs for youth and women strengthened local economies. KACE now stands as a model for how inclusive, market-led investments create sustainable productivity growth.

Photo: Sasakawa Africa Association



PRIORITY 2 – EXPAND ACCESS TO ROBUST AND RESILIENT MARKETS

Producers at all scales must be able to access competitive input and output markets. Price discovery, minimized search costs, and information transparency help producers to make informed decisions about the inputs required to optimize productivity and profitability, while assessing whether the benefits of a particular domain tool will justify the costs of adoption.

Policies have a direct effect on the prices that producers face—prices they receive for their agricultural products and the prices they pay for purchased inputs and nonagricultural goods (Hendricks et al., 2023; Nakelse et al., 2018). Transportation, ICT, storage, and financial infrastructure also play a key role in input and

output prices. For example, in lower-resource settings, producers often face suppressed commodity prices when they cannot store their crops until market conditions improve. Factors such as distance to markets, availability of storage facilities, access to existing and new technologies, products, and services, ability to finance these tools, and access to reliable market data influence production decisions.

Lack of market access can also exacerbate post-harvest losses, particularly for perishable goods that require cold chain logistics. These high-value, nutrient-dense products are essential for both producer incomes and consumer nutrition. Therefore, investing in market access infrastructure can incentivize productivity enhancements while supporting producer livelihoods and advancing food and nutrition security goals.

POLICY	Priority 2 Actions INVESTMENT	RESEARCH
<p>Build robust, streamlined, outcomes-based regulatory frameworks that will accelerate go-to-market for new technologies that push domain frontiers.</p> <p>Collaborate with universities and scientists, using AI tools to analyze evidence and align policy with science.</p> <p>Harmonize and streamline producer policy supports to de-risk investment when entering new markets or adopting new inputs.</p>	<p>Invest in Systems Integration infrastructure that will generate multiple benefits. For example, oyster restoration in coastal waters can improve water quality and ecosystems while creating oyster meat for markets, provided the right processing equipment and markets are available.</p>	<p>Fill critical evidence gaps needed to make viable ecosystem service markets that can be supported by policy and sufficiently remunerate producers for production transitions.</p> <p>Advance research on technologies and infrastructure needed for the Systems Integration domain goals – such as processing equipment for low-carbon-intensity biofuel feedstocks.</p>



Photo: AATF

INPUT INTENSIFICATION

Input Intensification through Crop Improvement and Mechanization Boosts Yields and Transforms Smallholder Farmer Livelihoods In Africa

The African Agricultural Technology Foundation (AATF)

AATF demonstrates how African agriculture can transition from land expansion to sustainable intensification. TELA® Bt maize—combining drought tolerance with pest resistance—achieved 88% yield increases for Nigerian farmers in 2024 without expanding farmland. Complementing this, gender-responsive cassava mechanization reduced labor by 80% while tripling yields from 9 to 25 tonnes/hectare, reaching 10,000 farmers across 30,000 hectares. These innovations—integrating improved genetics, mechanization, training, and digital solutions—demonstrate the shift from input expansion to input intensification paradigms, proving that Africa can achieve significant total productivity growth through technology adoption rather than unsustainable land conversion.

PRIORITY 3 – STRENGTHEN REGIONAL AND GLOBAL TRADE

Regional and global trade can push out domain frontiers, drive adoption, and facilitate transitions to later-stage domains by opening up larger markets, creating opportunities for specialization, and facilitating the flow of productivity-enhancing tools. Access to regional and international markets also enhances competitive prices, which incentivize investment in improved inputs and technologies. Trade also facilitates the exchange of knowledge, innovations, and best practices across borders, driving productivity gains. Additionally, global trade fosters competition, which pushes producers to enhance their efficiency and quality standards.

Aligning trade agreements with transparent policies, lowering trade costs, liberalizing trade, and consistently enforcing regulations strengthen regional and global trade to create returns to

TFP growth. For instance, in 13 African countries, evidence shows that reducing trade-distorting agricultural support coupled with good governance can increase TFP growth (Sunge & Ngepah, 2020). While national policies contributed more to output growth, South-South trade produced substantial productivity gains, matching or in some cases surpassing South-North trade benefits. This emphasizes the importance of regional trade, particularly on the African continent (Sunge & Ngepah, 2020).

Efforts to strengthen regional and global trade should account for key factors that can shape the extent of trade’s influence on TFP growth. For example, capital formation and a strong institutional environment can amplify trade’s positive effects on agricultural TFP. Conversely, high levels of debt may hinder productivity gains (Teweldemedhin & Van Schalkwyk, 2010; J. Zhu et al., 2022).

POLICY	Priority 3 Actions INVESTMENT	RESEARCH
<p>Harmonize sanitary, phytosanitary, and digital trade standards through cross-border ‘green lanes’ that accelerate flows of agricultural goods and technologies.</p> <p>Developing Adopters and Leapfroggers should negotiate regional trade corridors with digitally-enabled border systems to cut clearance times and boost flows of domain tools.</p>	<p>Mobilize blended financing to support smallholder integration into regional and global trade networks.</p>	<ul style="list-style-type: none"> • Advance machine learning-based risk assessment models to streamline border clearance and compliance. • Build cross-country research collaborations to identify trade bottlenecks and quantify the benefits of harmonized standards.

PRIORITY 4 – REDUCE LOSS AND IMPROVE QUALITY OF OUTPUTS

Reducing loss and waste and improving output quality contribute to agricultural productivity growth by increasing both the value and quantity of usable output from the same or fewer inputs. In particular, the reduction of food loss increases land and water use efficiency, particularly when losses originate upstream (Cattaneo et al., 2021). Higher quality outputs attract higher market prices, which creates a positive feedback loop for producers that

incentivizes investment in productivity-enhancing tools for higher value goods. As pressures from climatic variability, pests, disease, and limited access to resources such as affordable financing continue to intensify, it is essential to tailor loss and waste reduction policies and technologies to specific commodities and local contexts. If complemented with producers’ knowledge and experience, significant value can be captured from reduced waste and improved product quality—especially in regions where TFP growth is lagging.

POLICY	Priority 4 Actions INVESTMENT	RESEARCH
<p>Align digital traceability systems with public administration systems to safeguard food quality, reduce loss, and build consumer trust.</p> <p>Developing Adopters and Leapfroggers could integrate post-harvest loss reduction targets into national agricultural strategies and procurement standards to incentivize systemic transitions.</p>	<p>Diversify technologies that create productivity gains alongside Systems Integration co-benefits, such as technologies that turn crop residues, food waste, or livestock effluent into biofertilizers, feed ingredients, or renewable energy.</p>	<p>Validate and adapt IoT-enabled hermetic storage, climate-controlled warehousing, and renewable refrigeration for diverse contexts.</p> <p>Provide concrete evidence about consumers’ true willingness to pay premiums for agricultural products grown using sustainability principles to inform evidence-based Systems Integration market development.</p>



DRIVING ADOPTION

Bayer ForwardFarming: Modeling Sustainable Intensification Around the World

Bayer Crop Science

In many fields, “seeing is believing”. Agriculture is no exception. Model farms can showcase the potential that lies in sustainable intensification and system integration for local crops and growing conditions. Bayer Crop Science’s ForwardFarming program supports independent farmers in advancing regenerative agriculture. These farms open their doors to other farmers, agricultural stakeholders, policymakers, journalists, civil society representatives, students, and others interested in learning about climate-resilient, profitable farming. The initiative currently comprises 20 farms in 13 countries and the farms have already hosted over 65,000 visits.

Graphic: Bayer Crop Science



SYSTEMS INTEGRATION

The Americas Bioeconomy: A Driving Force for Prosperity

The Inter-American Institute for Cooperation on Agriculture (IICA)

IICA is harnessing advancements in science, technology, and innovation and the convergence of technological disciplines to build the bioeconomy in the Americas through its Bioeconomy Innovation Platform. The program positions the bioeconomy's potential in major regional and international technical and political spheres; builds capacity of its member states to advance the bioeconomy; supports the design of policies, rules, and regulations for the bioeconomy sector; develops tools, direct technical support and promotion of South-South cooperation and regional knowledge networks; and supports the creation of investment projects for bio-based businesses. This platform directly contributes to agricultural productivity growth by enabling producers to extract greater value from existing biological resources through bioeconomy innovations, helping reverse the concerning slowdown in total factor productivity across the Americas.

Photo: IICA

PRIORITY 5 – CULTIVATE PARTNERS AND COOPERATION

Bringing together stakeholders from across value chains, sectors, and backgrounds to pool resources, share knowledge, and drive innovation will create a multiplier effect for pushing frontiers, adopting domain tools, and transitioning to later-stage domains. Partnerships activate strong innovation systems and accelerate the development and dissemination of technologies, practices, and knowledge by tailoring productivity-enhancing tools for different contexts. Cooperation also facilitates best-practices scaling and goal alignment. This ensures that producer livelihoods, social outcomes (such as improved nutrition and reduced gender

disparities), environmental protection, and agriculture-led economic growth go hand-in-hand with agricultural productivity growth.

Fostering strategic partnerships will enhance the returns that sustainable productivity growth will have for producers, society, the environment, and the economy. The GAP Report™ partners exemplify how collaboration improves producer livelihoods, women's participation, smallholder farmer inclusion, nutrition and food security, access to robust markets, environmental resource protection and conservation, and delivery of ecosystem services in tandem with productivity growth.

POLICY	Priority 5 Actions INVESTMENT	RESEARCH
<p>Invest in agricultural experiment station systems that facilitate multi-sectoral collaboration and de-risking for producers.</p> <p>Create incentives for public–private partnerships that meet clear targets to drive inclusive frontier expansion—embedding equity, youth, and gender outcomes in the incentive structure.</p>	<p>Co-finance regional centers of excellence to strengthen Efficiency Optimization and Systems Integration, pooling R&D resources and building innovation ecosystems (Fast Followers, Developing Adopters).</p>	<p>Conduct comparative studies of productivity frontier transitions across regions and develop tailored investment roadmaps.</p>

KEY TAKEAWAYS OF THE TFP GROWTH FRONTIER

Even though population growth is slowing, incomes are rising, diets are shifting, and demand for non-food uses of agricultural products are increasing: competition for land, water, and other resources are intensifying pressures on agricultural systems. At the same time, climatic variability, biodiversity loss, and geopolitical uncertainty are reshaping the landscape in which agriculture must operate. Addressing the TFP growth plateau—now averaging just 0.76 percent annually, far below the 2 percent required—is a unifying strategy for addressing these constraints while meeting the demands of our agri-food systems.

The TFP Growth Frontier provides a powerful new lens for diagnosing these challenges and charting actionable solutions. By mapping the dynamics of agricultural innovation and adoption across four technological domains – Extensification, Input Intensification, Efficiency Optimization, and Systems Integration – the model not only explains the drivers of the current productivity plateau but also reveals the pathways to reinvigorate total factor productivity growth globally, regionally, and locally.

Key takeaways regarding the TFP Growth Frontier:

- 1  **Productivity growth is multi-dimensional.** Sustained growth does not come from a single technology or practice but from coordinated advances across multiple domains, tailored to local conditions and supported by enabling environments.
- 2  **Innovation is necessary, and adoption is critical.** Proven tools often stall in the “valley of death,” never reaching the scale needed to drive measurable efficiency gains. Bridging this gap requires investment in knowledge systems, extension, financing, and infrastructure.
- 3  **Domains have ceilings—but frontiers can be pushed outward.** Biological, economic, and environmental limits eventually slow returns in each domain. Strategic, sustained public and private R&D is essential to extend these ceilings and unlock new waves of productivity growth.
- 4  **Transitions must be intentional.** Moving from one domain to the next demands targeted policies, adaptive financing, and strong market signals to reduce risk and accelerate adoption.
- 5  **Leapfrogging is possible.** Countries with strong digital infrastructure, institutional capacity, and political will can bypass intermediate stages of development and adopt advanced technologies earlier, accelerating progress.
- 6  **Policy and investment alignment is key.** From expanding market access to modernizing regulatory frameworks and building robust data systems, coordinated action ensures that innovation and adoption work hand-in-hand to drive sustainable productivity gains.

The TFP Growth Frontier is more than a conceptual model; it is a call to action. With deliberate, evidence-based investment in innovation, adoption, and integration, agriculture can unlock the next era of productivity growth—one that delivers resilience, equity, and sustainability alongside efficiency. The choices made today by governments, industry leaders, researchers, and producers will determine whether agricultural systems can rise to meet the challenges of tomorrow.

THE GAP INITIATIVE AT VIRGINIA TECH

The Global Agricultural Productivity (GAP) Initiative at Virginia Tech motivates action and investment to accelerate sustainable agricultural productivity growth at all scales of production to create returns to farmers, society, the economy, and the environment.




Through collaboration, education, and advocacy, the GAP Initiative works across sectors to advance a future where every farmer has access to proven, appropriate productivity-enhancing tools—empowering agriculture to sustainably meet global needs by 2050. The GAP Initiative is a core pillar of CALS Global in the College of Agriculture and Life Sciences (CALS) at Virginia Tech.

THE GAP REPORT IS THE HEART OF THE GAP INITIATIVE.

Founded in 2010, the GAP Report™ uses publicly available data to interpret global trends in agricultural total factor productivity—a measure of how efficiently agricultural resources and inputs are used to produce output. The GAP Report™ draws on expertise from the private sector, international organizations, civil society, conservation and nutrition groups, universities, and research institutes to contextualize TFP growth trends and advocate for the importance of sustainable agricultural productivity growth across all scales of production.

The GAP Initiative is financially supported by Virginia Tech and private sector partners and receives technical support from these funders as well as organizations across the non-profit and public sectors. This collaborative support helps provide critical context and evidence on productivity-enhancing tools, approaches, and strategies.

The GAP Initiative is focused on driving measurable value for our partners. Over the next three years, we will use the annual GAP Report, robust research and analysis, focused and timely communication, and collaboration among our network of partners to:

-  Inform and shape policy dialogues.
-  Promote sustainable agricultural productivity-enhancing tools and knowledge.
-  Drive investment in and scaling of proven agricultural innovations.

GAP IQ



The GAP IQ™ platform will transform complex agricultural productivity growth-related data into actionable intelligence. By integrating diverse datasets, operationalizing best-in-class user experience design, and AI-driven analytics, the platform will optimize the TFP data value chain—removing friction and making insights more usable by policymakers, investors, decision makers, and researchers. This will enable faster, more informed decisions that will unlock sustainable agricultural productivity growth.

The platform is built on Google's advanced technologies (BigQuery, Looker, Gemini AI, and Vertex AI) and Appnovation's expertise in user-centered design.

GAP INITIATIVE SUPPORTING PARTNERS



GAP REPORT SUPPORTING PARTNERS



GAP ACCELERATORS



GAP INITIATIVE TECHNICAL PARTNERS



GAP INITIATIVE RESEARCH PARTNERS

