Chapter 2
Productivity in Agriculture for a Sustainable Future

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2.1 The Global Agricultural Imperative

In 2050, the number of people living on our planet will grow to nearly 10 billion, and that could double the demand for food, feed, fiber, and biofuels from 2005 levels (von Lampe et al. 2014). It is imperative that this demand be met in a way that is economically viable, environmentally sustainable, and socially beneficial.

Our food and agriculture systems face enormous challenges to sustainably producing sufficient, nutritious affordable food, feed, fiber, and biofuel for a growing world. At present, agriculture is the largest user of water globally; agriculture also is the single largest use of land, covering a third of the planet's surface. Competition between food production and other uses of water and land will increase in the coming decades. In addition, climate change threatens agricultural productivity due to increased temperatures and shifts in weather patterns (Box 2.1), thereby making it difficult for crops and livestock to grow and thrive and for agricultural laborers to endure the physical challenges.

Box 2.1 The Challenge of Climate Change for India's Farmers (Naresh et al. 2017)

India's farmers are struggling as temperature and rainfall patterns become hotter, drier, and wetter. By the end of the century, the mean summer temperature in India could increase by five degrees Celsius. The number of days of extreme heat could increase by more than a month, and the number of warm nights could more than double. The amount of rain is also

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expected to increase by as much as 40%, while the frequency of extreme rain events is also increasing, as well as the number and length of droughts.

Under these conditions, by 2035, yields for India's major food crops are

expected to decline by as much as 10%. Rising temperatures and the increase in extreme heat will make living and working conditions unbearable and reduce the productivity of farmers and agricultural laborers. Livestock will also struggle with the heat, and nutrition of their fodder will be reduced.

Without support and adaptation, agricultural productivity in India could decline by as much as 25%; the productivity of small-scale rain-fed farms could decline by as much as 50%, posing formidable challenges to food security, human well-being, and economic and political stability.

Volatile agricultural business cycles also create challenges for farmers as they seek to manage risk and invest for the future. Conflict and migration generate famine and human suffering. And global health is compromised by malnutrition, poor diets, and disease.

The previous 10 years have witnessed unprecedented demand for agricultural commodities, driven by income increases and population growth in China and India, as well as demand for biofuels stimulated by high energy prices.

Over the decade 2017–2026, the OECD and the United Nations Food and Agriculture Organization (FAO) project that the rate of demand growth for all agricultural commodities will slow compared with the prior decade (OECD/FAO 2017). The rate of demand growth for cereal grains, meat, fish, and vegetable oil will be cut nearly in half, the notable exception being increasing demand for fresh dairy (Box 2.2 and Fig. 2.1). OECD and FAO attribute the decline in the rate of demand growth to moderating rates of economic growth, particularly in China, and a decline in demand for biofuels.

While the rate of demand growth may be slowing (compared to the previous 10 years), the overall demand for food and agriculture products is still rising, as is the global population. In fact, the highest demand growth for many agricultural

Box 2.2 Meeting India's Milk Demand (Steensland and Zeigler 2018)

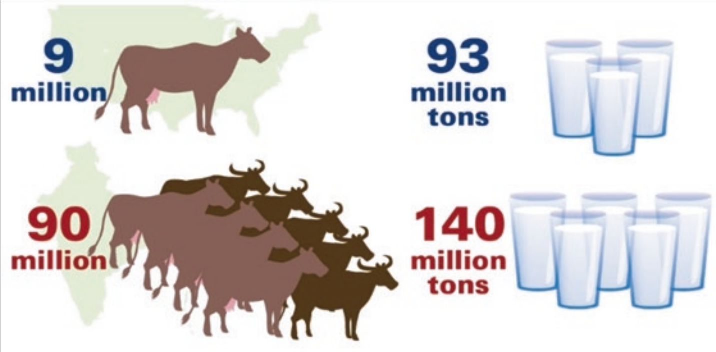

Fig. 2.1 Milk productivity in India and the United States. India has ten times as many dairy-producing bovines (cattle and buffalo) as the United States but produces only 50% more milk. (Data from FAOSTAT 2014). Figure: adapted from 2017 Global Agricultural Productivity Report (GAP Report), page 14)

Over the next decade, India will account for 54% of the increase in global demand for fresh dairy products, requiring an additional 56 million tons of milk. India is already the largest dairy producer in the world, but dairy cattle and buffalo productivity is low. In 2014, India had 50 million dairy cows and 40 million water buffalo, a total of 90 million animals producing 140 million tons of milk. Dairy cattle produce an average of 14,000 hectograms per animal, and buffalo produce 19,000 hectograms per animal (FAOSTAT 2014).

By contrast, the United States had just 9.2 million dairy cows and produced more than 93 million tons of milk, an average of 101,000 hectograms per animal (OECD/FAO 2017). Given the projected demand in India, improving the health and productivity of the current dairy cow and buffalo populations needs to be prioritized. Indian farmers and consumers are increasingly choosing buffalo over dairy cow milk (Landes et al. 2017). Consumers prefer the higher fat content of buffalo milk, and it brings a higher return to farmers. Buffalo are more adaptable to the changing climate in India, and they convert the low-quality indigenous grasses into milk more efficiently than cattle.

Improving genetics, feed, and animal care practices can provide more milk using fewer animals. Increasing access to mechanization for small- and medium-scale farmers would reduce reliance on cattle for draught power, allowing investments in milk production.

products is coming from regions most vulnerable to climate change, with high rates of population growth and low rates of agricultural productivity, such as South Asia and sub-Saharan Africa. These regions are characterized by small farms, with little access to productive inputs, and a substantial proportion of the rural workforce represented by women. As production increases to meet the growing demand, concerns are rising about the environmental impact these low-productivity systems will have on the natural resource base, along with rising greenhouse gas emissions.

2.2 What Is Productivity in Agriculture?

For agricultural producers of all scales, there are multiple approaches to meeting the current and future demand for agricultural products:

- *Land Expansion* – Producers use more land to produce more agricultural products and, in some cases, convert forest to cropland or rangeland.
- *Irrigation* – Producers deploy or extend irrigation systems to protect land against drought and improve its productive capacity, which may permit multiple cropping seasons. If not carefully managed, groundwater may be depleted.
- *Intensification* – Producers increase applications of fertilizer, machinery, labor, seeds, herbicides, or other inputs on existing land to grow more crops or raise more livestock.

Meeting demand in a way that reflects the needs of producers and consumers today, while safeguarding future agricultural capacity, is best achieved another way:

- *Productivity Growth* – Adopting technologies and production practices that result in more output from the same amount, or less, inputs. This can be measured as *total factor productivity (TFP)*.

While the terms are sometimes used interchangeably, agricultural "productivity" is distinct from "output" and "yield." Output is the gross amount produced, and yield measures the amount of output per unit of production, usually land. TFP (Fig. 2.2) is the ratio of agricultural outputs (gross crop and livestock output) to inputs (land, labor, fertilizer, feed, machinery, and livestock). TFP measures changes in the efficiency with which these inputs are transformed into outputs.

TFP is calculated using measurable inputs, so water and seeds are not factors in the equation. Eighty percent of global agriculture is rain-fed, making it difficult to quantify water usage. It is also difficult to quantify seed usage since millions of farmers, particularly those at smaller scales, use open pollinated varieties (OPVs), which are derived from the grain of the previous harvest.

By measuring TFP, as opposed to yields or output, we begin to understand the extent to which increased output is due to better use of these critical resources. Policymakers, development agencies, researchers, and producers use TFP to identify where improvements are needed in agricultural production systems and to determine which investments and policies increase productivity and enhance sustainability.

Producers, governments, and agribusinesses who pursue this course are not just interested in whether agricultural output is growing but to what extent increased output is due to better use of existing resources through the application of improved products, technologies, and practices – *essentially*, *how innovative their operations are.*

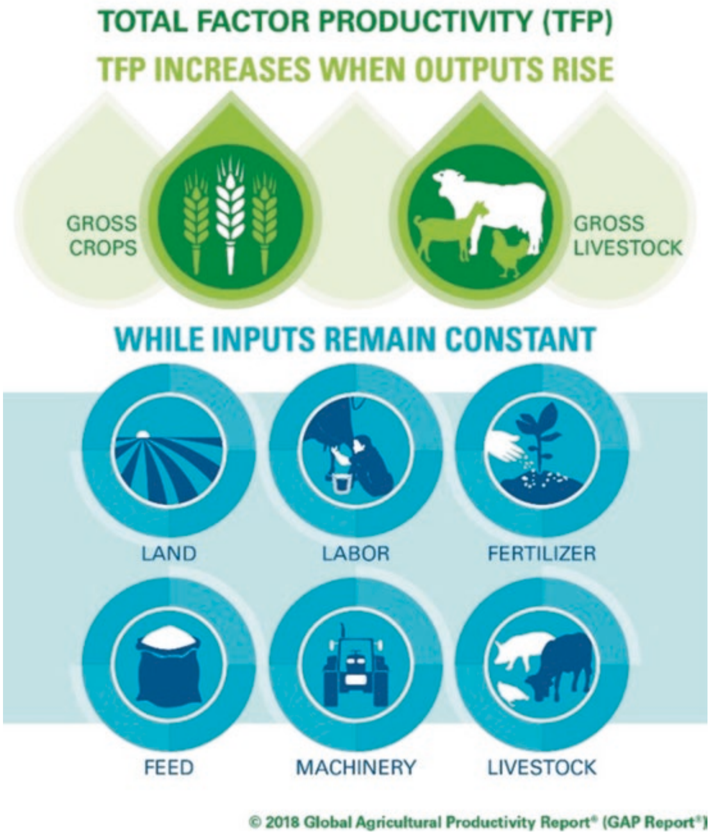

Fig. 2.2 Total factor productivity. (Source: 2018 Global Agricultural Productivity Report (GAP Report))

Examining TFP is the best way to get that information, which can be enormously useful in identifying where improvements are needed in agricultural production systems, how to make investment decisions, and what policies support more productive and sustainable agriculture.

2.3 Productivity and Innovation in Practice

For crops, improved TFP results from adopting innovations like higher-yielding, pest-resistant, and/or drought- and flood-tolerant seed varieties. The growing bio-innovation sector includes precision use of microbes (bacteria and fungi) to help crop farmers generate more yield on the same land. Microbes also protect plants from dry conditions and increase yield, as well as protect plants from pests.

Agricultural extension agents or agricultural retail service providers can equip growers with knowledge of best practices that enable more efficient and timely cultivation techniques, improve soil and water quality, and improve crop yields. TFP growth also comes from widespread adoption of precision data and information technologies in farm equipment to target applications of fertilizer, water, and crop protection. Having access to geo-referenced data also enables farmers to improve soil quality, plan for crop rotation cycles, and place less productive land into conservation.

In livestock production, TFP increases when favorable genetic traits in animals are selected and bred and when animals receive better overall husbandry, vaccinations, and high-quality feeds that deliver more nutrition per volume. In forestry, genetically improved trees provide faster-growing products for earlier harvesting and more volume per tree.

Ensuring that farmers and producers of all scales and sizes gain access to better innovation, technology and training, and knowledge for best practices will help foster greater TFP and reduce impact on the soil, aquifers, and other underground water bodies and water and air quality, as well as effectively use increasingly scarce labor in agricultural operations.

TFP looks beyond simply *how much* farmers are producing. It reveals *how efficiently* they are producing it and indicates how well they are conserving available resources to meet future needs. Productivity growth in agriculture lowers the cost per unit of output, helping producers succeed in today's competitive business cycle, and enables agri-food systems to provide lower prices for consumers.

Farmers use productive technologies and practices such as improved seeds and farm equipment, genetically improved livestock, and good animal husbandry to increase output while conserving land and water and protecting soils for future generations. In addition to promoting competitiveness and conservation, productive technologies and good practices also support the *UN Sustainable Development Goals (SDGs)* to end hunger and malnutrition, protect the safety of the water supply, and reduce greenhouse gas emissions.

Case studies throughout this chapter demonstrate how farmers of all scales, producing a variety of products in different geographies, are conserving and protecting their soil and water resources while reducing their climate impact. Innovations highlighted include drought-tolerant new plant varieties that enable poor farmers in dryland areas to grow in stressful conditions (Box 2.3); precision agriculture technologies that enrich soil in the field and keep nutrients out of streams; and animal care innovations and practices that improve the health and productivity of each animal while reducing emissions from livestock production.

Box 2.3 Corn Productivity Feeds Vietnam (Zeigler and Steensland 2017)

Corn is already the second largest crop in Vietnam after rice, yet the country still imports between five and seven million tons of corn each year to feed livestock for growing consumer protein demand. With little additional land available for production, farmers must improve corn productivity on existing

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land to seize the market opportunity to supply livestock feed. Better production practices and better seeds are needed.

As part of Monsanto (now Bayer AG) Vietnam's sustainable development efforts, more than 200,000 farmers have received training since 2015 on good agronomic practices and hybrid corn seed selection. Seeds with beneficial traits improved through conventional breeding and advanced biotechnology are now becoming available for many farmers in Vietnam.

Vietnamese farmer, Huynh Van Hue, enjoys a successful corn harvest using the rice-to-corn rotation protocol.

High-yielding improved corn seeds such as hybrids and stacked trait biotechnology (seeds engineered to deliver to farmers both insect protection and herbicide tolerance traits) help farmers grow more while requiring less labor to remove weeds and apply crop protection. The improved corn is particularly resilient against three harmful pests: Asian corn borer, common cutworm, and corn earworm.

To help farmers make the transition from rice to corn, Monsanto agronomists and rice farmers developed a series of best agronomic practices, the *Dekalb® Cultivation Rice-to-Corn Rotation Protocol*, that was selected as a preferred cropping system by the *Vietnamese Ministry of Agriculture and Rural Development*. Farmers in pilot programs used this protocol across several departments of Vietnam and increased their incomes by up to 400% while supplying more corn for livestock feed. New jobs and businesses such as corn drying and feed mill development are becoming part of the growing corn value chain.

The Ministry has set a goal of transitioning 668,000 hectares of rice-growing land to corn production in the northern region of Vietnam by 2020. Farmers in other regions of the country are also being supported as they diversify to more resilient, high-value crops and livestock while sustainably intensifying rice production in the most suitable areas.

2.4 Productivity Rises, with Room to Grow

TFP accounts for the largest share of growth in global agricultural output today (Fig. 2.3). In the 1960s, the Green Revolution introduced high-yielding new plant varieties of wheat and rice to millions of small farmers in Mexico, India, and other developing countries, along with access to fertilizers, irrigation, and machinery. As farmers began to use those inputs more efficiently, the contribution of inputs per land area to agriculture output declined (orange bar), and TFP's contribution increased (green bar).

Agricultural productivity supports the needs of producers, consumers, and the environment. Productive use of inputs and capital helps farmers control costs during volatile business cycles. Consumers benefit from lower food prices and natural resources, particularly land and water, are conserved.

However, the most recent 10-year period of available data (2006–2015) reveals that TFP's contribution to output growth is declining and more output has been generated by placing additional land into production. (Compare the two columns, 2001–2010 and 2006–2015, in Fig. 2.3.) Farmers around the world expanded their production in response to lower global grain stocks and higher prices during this period.

In high-income countries, improvements in productivity expand output while reducing inputs used in agriculture and dramatically freezing land expansion (Fig. 2.4). Innovations that have raised productivity include advanced crop technologies (genetically modified seeds, novel genetic and breeding approaches, and improved crop protection products) along with advanced livestock breeding, improved animal feed and care, precision agriculture, and better nutrient management. In the most recent decade, however, the downward trend in productivity growth can also be seen in high-income countries. (Compare the two columns, 2001–2010 and 2006–2015, in Fig. 2.4.)

Low-income countries have mirrored the global trend in TFP growth and enjoyed a substantial increase in agricultural output since the 1960s (Fig. 2.5). However, since the 1980s, opening new land for agricultural production (red bar) remains the primary driver of agricultural output. TFP's contribution to agricultural output has grown during the most recent 10-year period. (Compare the two columns on the right in Fig. 2.5.)

Nonetheless, economic and political forces have driven land expansion in low-income countries: transitions to market-based economies, the introduction of input subsidies and prices supports, growing populations needing more land to cultivate, and the extension of irrigation. While some land is suitable for agricultural expansion, greater productivity on existing cultivated land needs to be prioritized to minimize agriculture's impact on soil, water, forests, and wildlife.

Low labor productivity on small-scale farms, predominantly found in low-income country agricultural systems, largely accounts for the higher inputs per hectare of agricultural land results (Fig. 2.5, orange bar). Small-scale farms are labor-intensive due to insufficient off-farm or urban employment opportunities that could absorb the excess labor in rural areas. Small-scale farmers also struggle to

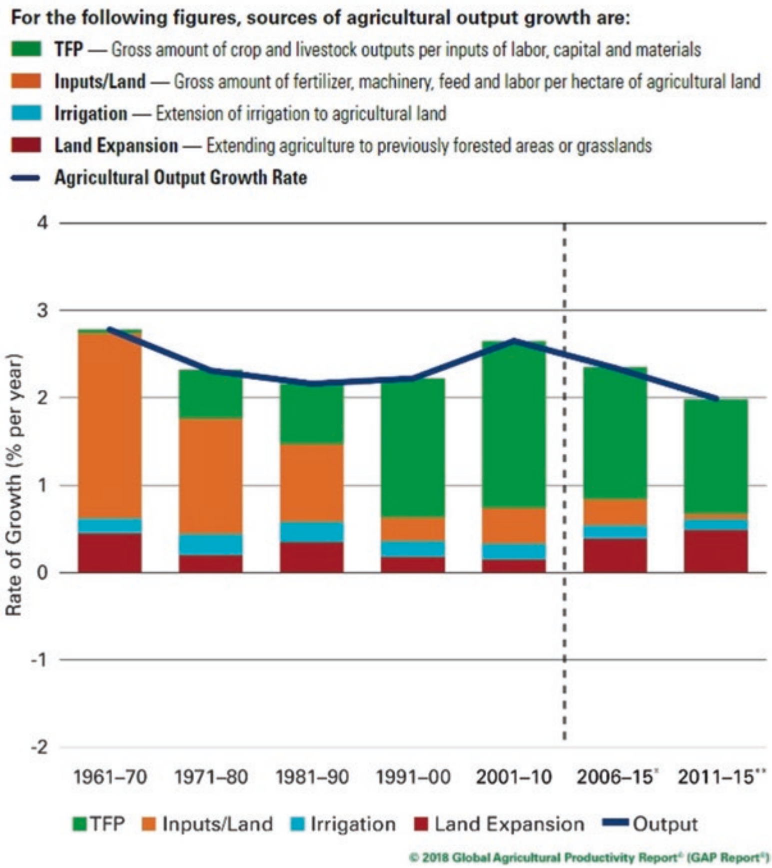

Fig. 2.3 Sources of growth in global agricultural output, 1961–2015. *Depicts data for the most recent ten-year period. **Depicts data for the most recent five-year period. (Source: USDA Economic Research Service (2018))

purchase or rent machinery at competitive prices relative to their labor cost and, in addition, lack the market insight needed to capture better prices for their produce. This contributes to high rates of rural poverty and food insecurity.

2.5 Agricultural Productivity and the Sustainable Development Goals

The United Nations' 17 Sustainable Development Goals (SDGs) took effect at the beginning of 2016, launching the countdown to achieve inclusive, sustainable development and economic growth by 2030. Many SDGs have clear implications for agriculture, while agriculture and forestry play a central role in the strategy to

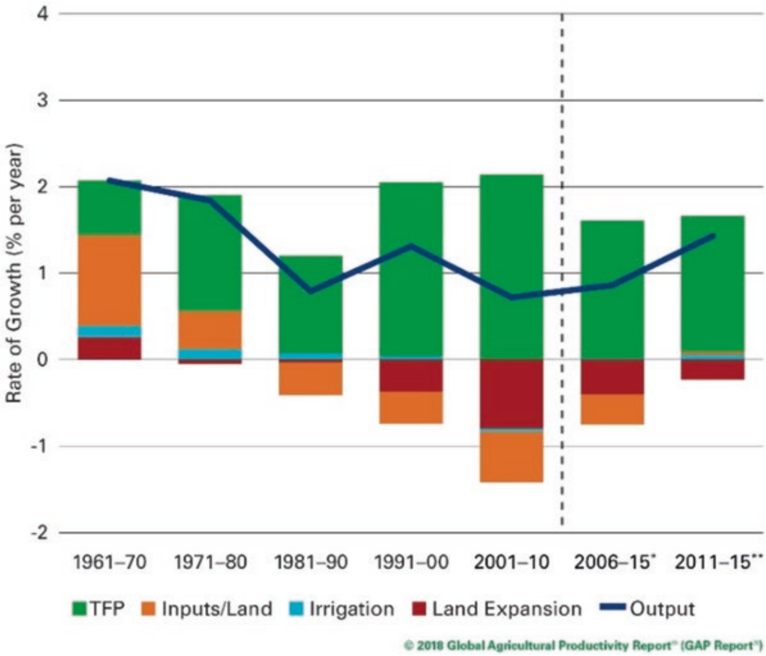

Fig. 2.4 Sources of growth in agricultural output: high-income countries, 1961–2015. *Depicts data for the most recent ten-year period. **Depicts data for the most recent five-year period. (Source: USDA Economic Research Service (2018))

achieve many of the goals. Most notably, *Sustainable Development Goal 2 (SDG 2)* calls the world community to "end hunger, achieve food security and improved nutrition, and promote sustainable agriculture." As part of a comprehensive set of actions, the *UN's 2030 Agenda for Sustainable Development* calls for "doubl[ing] the agricultural productivity and incomes of small-scale food producers, particularly women, indigenous people, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets, and opportunities for value addition and non-farm employment" (von Lampe et al. 2014).

Accelerating agricultural productivity must be at the core of a comprehensive strategy to sustainably feed the world (Box 2.4). With more than three-quarters of the world's poor being heavily dependent on agriculture for their direct subsistence food needs as well as for their incomes, agricultural development through productivity improvements and higher incomes is one of the most powerful ways that farmers, pastoralists, and fishers can rise out of poverty and improve their nutrition and health.

Productivity benefits producers of all sizes by improving the resilience and competitiveness of their operations. Productivity also enables better stewardship of land, water, and other natural resources.

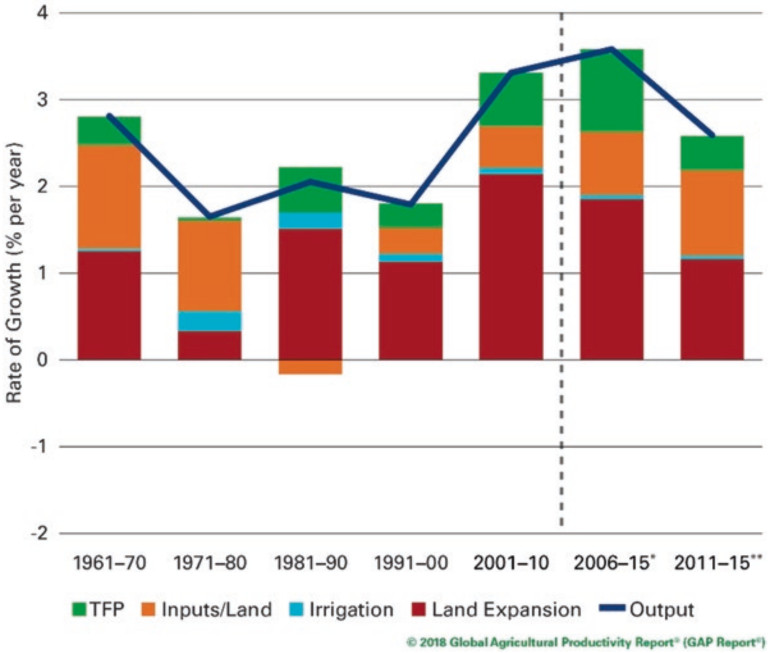

Fig. 2.5 Sources of growth in agricultural output: low-income countries, 1961–2015. *Depicts data for the most recent ten-year period. **Depicts data for the most recent five-year period. (Source: USDA Economic Research Service (2018))

Box 2.4 Doubling Agricultural Productivity Is the Right Goal

The projected slowdown in demand for food and agriculture products over the next decade has prompted calls for a reduction in the agricultural output targets for 2050 (Hunter et al. 2017). Yet a large and growing body of sophisticated modeling by agricultural economists examining long-term scenarios for agriculture, food, and the environment indicates that it may be too soon to consider revising these goals downward.

The Agricultural Model Intercomparison and Improvement Project (AgMIP) is an international collaborative effort to improve agricultural economic models. AgMIP coordinates regional and global assessments of climate impacts and uses multiple scenarios for crop and livestock production across differing geographies to explore the effects of uncertainty, data selection, and methodology on the models' results.

AgMIP's analysis of ten leading global multi-sectoral projection models found that world agricultural production of crops and livestock between 2005 and 2050 will need to rise by between 60% and 111%, with demand growth particularly strong for ruminant products (cows, sheep) as well as for com-

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modities used in the production of biofuels – sugar, coarse grains, and oilseeds (von Lampe et al. 2014). (The OECD/FAO prediction of a decrease in the rate of demand growth for food and agriculture products extends only to 2026, not to 2050.)

Most importantly, AgMIP points to the impact climate change will have on the ability of agriculture to meet future demand. The ten models suggest that climate change will generate higher prices for agricultural commodities in general and particularly for crops (von Lampe et al. 2014). The impact of climate change must be considered to avoid a downward bias in projected supply estimates.

2.6 Tracking Productivity: The GAP Index™

The 2018 Global Agricultural Productivity (GAP) Index™ reveals that for the fifth straight year global agricultural productivity growth (TFP) is not accelerating fast enough to sustainably meet the food, feed, fiber, and biofuel needs of nearly 10 billion people in 2050.

In 2010, the Global Harvest Initiative (GHI) calculated that global agricultural productivity (as measured by TFP) must grow by an average rate of at least 1.75% annually to double all agricultural output *through productivity growth* by 2050. The US Department of Agriculture's Economic Research Service (USDA ERS) estimates that since 2010, TFP growth globally has been rising by an average annual rate of only 1.51% (Fig. 2.6).

The GAP Index™ was created in collaboration with Dr. Keith Fuglie of USDA Economic Research Service. Dr. Fuglie provides annual updates of TFP data for the GAP Report.

The average annual TFP growth rate in low-income countries is particularly troubling. Sustainable Development Goal 2 (SDG 2) calls for doubling productivity for small-scale farmers in the low-income countries. The current annual rate of TFP growth in low-income countries is only 0.96%, down from 1.5% 3 years ago. This is well below the TFP growth rates needed to achieve the SDG 2 target of doubling productivity for small-scale farmers in the lowest-income countries by 2030.

If this trend continues, farmers in low-income, food-deficit countries (where population growth is rapidly rising) will use more land and water to increase their output, straining a natural resource base already threatened by extreme weather events and climate change. Many low-income countries will need to import food but lack sufficient income to purchase enough to meet the needs of their citizens. Poor urban households will bear the brunt of higher food prices in these countries, but they will also impact low-income rural populations since they are net food buyers. Some of the food demand will not be met, and millions of people will be debilitated by hunger and malnutrition.

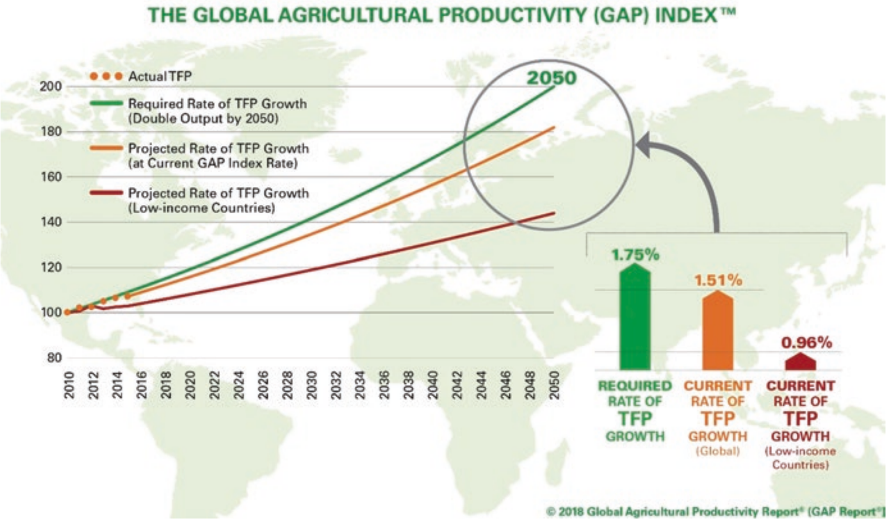

Fig. 2.6 The Global Agricultural Productivity (GAP) Index™ (2018). (Source: Food Demand Index is from Global Harvest Initiative (GHI) (2018); Agricultural Output from TFP Growth is from USDA Economic Research Service (2018))

2.6.1 Regional TFP Growth Rates Raise Concerns

Rates of productivity growth vary greatly by region, as can be seen by comparing food demand indexes against projected agricultural output from TFP growth for the period 2000 to 2030. Figure 2.7 compares the percentage of the estimated food demand for 2030 that can be met with projected TFP growth for six world regions and China.

At current rates of TFP growth, sub-Saharan Africa (SSA) will meet only 8% of its food demand through productivity (Fig. 2.7). Trade plays a key role in closing Africa's food demand gap; 50% of its vegetable oils, 35% of its poultry meat, and 23% of its sugar requirements are imported (OECD/FAO 2016). Without significant increases in agricultural productivity growth, African countries will not meet their SDG targets for reducing hunger, malnutrition, and poverty and will rely more on trade to meet growing demand and most likely will continue to expand land area under cultivation to grow more food, threatening wildlife habitat and releasing soil carbon from forest conversion to cropland. In addition, an increasing financial burden will be imposed on them in order to increase their imports of raw food materials which oftentimes are paid for in foreign currencies.

With 60% of the world's population and considerable economic diversity, the Asian regions (South Asia, Southeast Asia, East Asia, including China) exhibit varying degrees of capacity to meet food demand through productivity.

China has prioritized agricultural development and food security and has achieved great progress in reducing hunger. Yet with little arable land and growing affluence, China will require more investments in productivity and more trade to meet future demand.

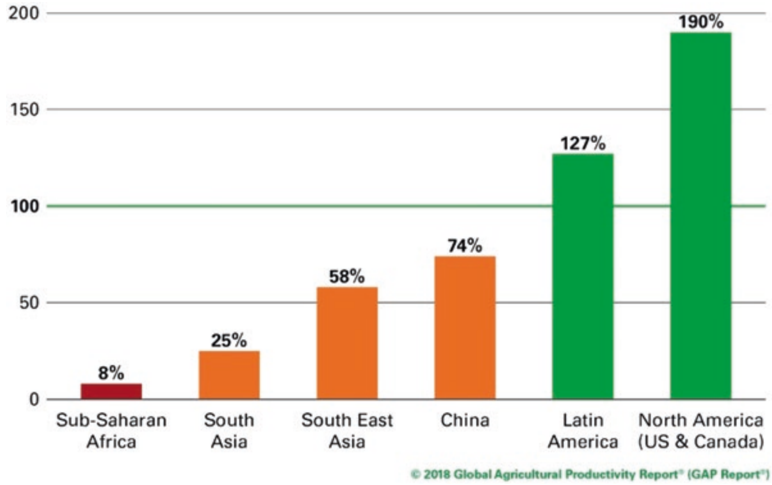

Fig. 2.7 Percent of food demand met through productivity (TFP) growth in 2030. *Note on methodology*: The projection of agricultural output from TFP growth uses USDA ERS (2017) estimates of average TFP growth during 2004–2014 and assumes this is maintained through 2030. The projected growth in food demand uses UN estimates of population, World Bank estimates of GDP forecasts and PricewaterhouseCoopers LLP (PwC) estimates of GDP growth in PPP, and estimates of the income elasticity of food demand from Tweeten and Thompson (2008).The income elasticity of food demand indicates the share of the growth in per capita income that will be spent on food. Multiplying the income elasticity by the growth rate in per capita income gives the growth rate in per capita food consumption holding food prices fixed. Adding this to the population growth gives the total growth in food demand for a given price level. (Source: Food Demand Index is from Global Harvest Initiative (2017). Agricultural Output from TFP is from USDA Economic Research Service (2017))

South Asia will only meet 25% of its growing demand through productivity by 2030. Despite increasing agricultural output since the Green Revolution, India still relies on large amounts of inputs per land area and high labor inputs to produce food, rather than boosting productivity. Other Asian countries, such as Indonesia and Vietnam, could potentially reduce hunger and improve agricultural productivity, but face significant threats from climate change, requiring accelerated investments to keep up with the challenge.

Latin America (LAC) continues to position itself as a rising global breadbasket. At present TFP growth rates, LAC will be able to meet 127% of regional food demand through productivity growth, an increase of 11 percentage points since 2014. The LAC region and particularly the southern cone nations of Argentina, Brazil, Paraguay, and Uruguay comprise the world's largest net exporting zone of agriculture products (Regúnaga 2013). These countries and others in Latin America have the potential to vastly increase their productivity to sustainably supply food and other agricultural goods for their own populations and to a growing world. Harmonizing trade rules and improving the trade capacity of low-income countries, coupled with improvements in supply chains and infrastructure, will foster timely and beneficial trade to close food and agriculture demand gaps.

In 2030, North America is projected to reliably supply safe, abundant food for the world, producing nearly as twice as much food to meet its own food demand. However, the potential for a new era of trade protectionism has sent a chill through agricultural producers who fear they will lose access to traditional trade partners or fail to access new markets at a time when prices are low and farmers are struggling. Investments in R&D would become more critical than ever under these circumstances (Box 2.5).

Box 2.5 Public Research Sparks Innovation and TFP

Due to agriculture's dependence on limited resources like water and land, it may be unique in its reliance on productivity and innovation to meet the rapidly growing demand of consumers by 2050 (Fuglie 2018). Agri-food innovation systems rely heavily on public agricultural research and development (R&D) and extension systems as well as regulatory frameworks that incentivize risk taking innovation and investment. Such agricultural R&D investments require long gestation periods of more than a decade to realize the full benefits that these investments generate. Over time, they pay large dividends, including higher profits for farmers, more abundant food supply at lower cost for consumers, and more opportunities and a higher quality of life in rural communities.

Filomena do Anjos is a senior lecturer and veterinarian at Eduardo Mondlane University, Mozambique. She is developing a more economical poultry feed, as more than 70% of rural families in Mozambique raise chickens. Photo credit: Carlos Litulo

Agricultural R&D along with extension programs are essential public goods and the principal drivers of total factor productivity (TFP) growth. Public sector R&D and extension programs deliver innovation and information to agricultural producers. They provide access to proven techniques such as conservation agriculture and animal care practices to improve the sustainability and resilience of their operations. While farmers innovate on their

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farms, experimenting with practices that can boost their own production, individually they do not have the capacity to conduct long-term research and development activities.

Public R&D provides foundational results that the private sector can further develop to improve specific crops, livestock, machinery, or food manufacturing industries. R&D and extension services help producers control costs, reduce loss and waste, and become resilient to weather challenges and climate change while conserving natural resources.

Countries that build national agricultural research systems (NARS) capable of producing a steady stream of innovations suitable for local farming systems, such as Brazil's EMBRAPA, have generally achieved higher growth rates in agricultural productivity than countries that do not make these investments.

Future TFP growth in North America will be driven by innovations such as advanced crop and livestock breeding and data systems that monitor plant growth and animal health. However, public sector investments in the research and development (R&D) that drive agricultural innovation has slowed in the United States and in many high-income countries (Fig. 2.8).

For high-income countries, the growth rate in spending for public agricultural R&D averaged 4% annually between 1960 and 1990. Between 1990 and 2009, the growth rate declined to just 1.3% annually and *then began to contract between 2009 and 2013, declining on average 1.5% annually.*

Public R&D provides discoveries that are the foundation for further private sector innovation; lower public investments constrict the innovation pipeline. Private sector research investments, while significant, cannot make up the public R&D funding gap. Increased public sector R&D investments are needed to reinvigorate productivity growth. Additionally, as urbanization increases, so does competition for land and water resources. Continued farm consolidation will create some additional efficiencies, but land and water-use policies must balance the resource needs of agricultural producers with those of their urban customers.

2.6.2 Growing Productivity While Protecting Against Risk

Globally, productivity growth must continue to be a priority to sustainably meet the demand for food, feed, fiber, and biofuel. Yet productivity alone is insufficient to achieve economically, environmentally, and socially sustainable food and agriculture systems.

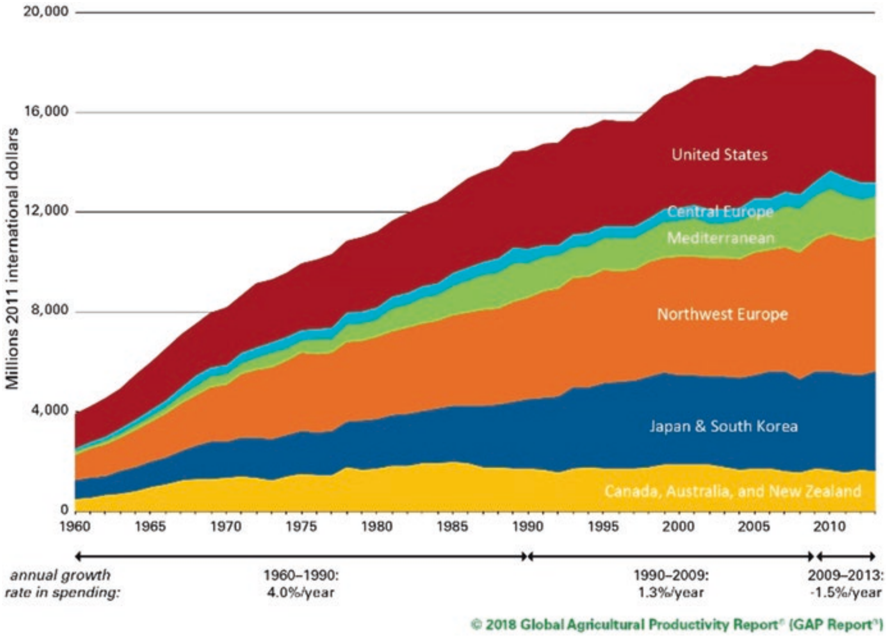

Fig. 2.8 Public agricultural R&D spending in high-income countries, 1960–2013. (Source: USDA ERS analysis of data from the Organization for Economic Co-operation and Development, Pardey and Roseboom (1989), World Bank and numerous supplementary sources. Paul Heisey and Keith O. Fuglie, "Agricultural research investment and policy reform in high-income countries." USDA ERS Research Report Number 249, May 2018)

Food and agriculture systems are vulnerable to a variety of risks, including extreme weather events and climate change, market volatility, and political instability. During times of crisis, agricultural producers seek to minimize their losses without putting their future productivity at risk. Good innovations and an enabling policy environment can ensure they stay productive during seasons of risk. This also helps stabilize the supply and price of food and agriculture products (Box 2.6).

Public and private insurance programs, such as crop insurance or weather index insurance, help preserve producer incomes and enable them to keep their most productive assets and to more effectively manage risk. Some producers participate in conservation programs that reward them for protecting their soil and water resources. Those without access to insurance and conservation programs face difficult choices. During hard times, small-scale farmers usually raise cash by selling cattle and equipment or by leasing their land; the poorest farmers have little to sell. Instead, they reduce their consumption of food and may resort to pulling children from school and into labor. They also reduce the already less than optimal proportion of family income spent on providing access to health services for children and women, particularly lactating and pregnant women. These coping strategies have negative, long-lasting impacts on the health and economic prospects of the family as well as their farm operations.

Consumers also face risks from economic instability or food price shocks. Governments are establishing social protection programs to stabilize households experiencing food and income insecurity. Some countries rely on national reserves to feed their population and manage food prices. Ensuring that agricultural trade remains open is essential to keeping food prices stable, especially when commodity stocks are low.

Box 2.6 Social Protection Programs Reduce Risk (Daidone et al. 2014)
Social protection programs, such as cash grants, provide the poorest rural residents with income stability and food security while also reducing their reliance on agricultural wage labor and freeing them up to invest time and resources in their own farms, to develop off-farm enterprises, or to pursue training for non-agricultural employment. In 2010, the *Zambian Ministry of Community Development for Mother and Child Health (MCDMCH)* piloted a *Child Grant Program (CGP)* in three provinces, where the program gave households with children under the age of 5 a total cash grant of $12 per month. Payments were made monthly and without condition.

The Child Grant Program, a pilot project in the Eastern Province of Zambia, provided families who have children under the age of 5 with a monthly grant that helped stabilize family incomes, enabling parents to invest more time and resources in developing their farms and off-farm enterprises.

The program not only reduced the severity of poverty, but it changed the participants' perception of their own food and income security: the number of households that reported being better off than they had been 12 months earlier increased by 45%. Perhaps most encouraging was the increased investment in productivity-enhancing and labor-saving inputs and the increases in agricultural output by CGP beneficiaries. The value of the overall harvest increased by 50%, on average, with most of the additional production being sold. CGP households increased both their ownership of livestock (21%) and the diversity of their livestock.

Finally, the income stability of the cash grants enabled participants, particularly women, to reduce their wage labor hours and develop their own

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enterprises. The percentage of households that operated off-farm businesses increased by 17%. The CPG grants also had a significant multiplier effect: each Zambian kwacha transferred to a recipient generated 1.79 kwacha in the local economy.

In order to move people from "protection to productivity," social programs must be accompanied by investments and partnerships that improve producers' access to secure land tenure, transportation, electricity, and irrigation infrastructures and agricultural knowledge and innovations developed and disseminated by a robust research and extension system.

2.7 Food Wasted Is Productivity Lost

Reducing agricultural losses on the farm and food lost throughout the agricultural value chain avoids wasted resources and unnecessary greenhouse gas emissions.

On average, Americans throw away one pound of food each day, the equivalent of 30% of the calories they normally consume. Fruits and vegetables alone account for almost 40% of the waste, 17% is milk and dairy products, and 13.5% is meat (Conrad et al. 2018). These wasted foods are important sources of vitamins, minerals, protein, and calcium that promote healthy lifestyles and reduce healthcare costs. In addition, they represent a waste of all the water needed to produce them in the field and to process them in the value chains connecting farm produce with consumers.

Higher-income households tend to replace spoiled foods quickly, for example, purchasing another carton of strawberries during the next trip to the grocery store when the carton in the refrigerator goes bad. In those households, the lost nutrients are replaced and therefore more likely to be consumed. But the price of highly perishable foods can prevent many households from replacing spoiled food right away, so the opportunity to consume those nutrients is lost, along with the food.

Not only do spoiled foods end up in landfills producing methane, but they are a waste of the agricultural resources used to produce them.

A USDA study calculates that the equivalent of 30 million acres of cropland would be needed to produce the food and animal feed for livestock products (dairy, meat, and eggs) that Americans throw away each year (Conrad et al. 2018). Nearly 4.2 trillion gallons of irrigation water is wasted, including 2.3 trillion gallons to produce the wasted fruit and vegetables alone. Wasted fruits and vegetables are responsible for most of the pesticide waste, while most of the wasted cropland and fertilizer is used to produce feed for livestock.

While beyond the scope of this chapter, wasted food is also a waste of agricultural labor, capital (mechanization), and public and private sector investments in the development of technologies for agricultural productivity and sustainability (Fig. 2.9). The economic and environmental costs of transporting, packaging, and storing food that eventually ends up in the garbage and landfills also need to be taken into account in the cost of wasted food.

Improvements must be targeted throughout every part of the value chain: better harvesting and storage practices, better livestock care to reduce disease, improvements to the cold chain and the transportation infrastructure it relies on, reductions in waste at the processing and retail levels, and changes in consumer behavior.

Reducing loss and waste on a wide scale depends on government investments in public goods, such as infrastructure. An enabling policy environment that supports private sector innovation in harvest and storage technologies and stimulates behavior change by consumers is also vital. In addition, there are opportunities to increase the productive use of unconsumed food and agricultural byproducts (Box 2.7). These are potential sources of bio-energy, animal feed, fertilizer, and new products.

Reducing loss and waste and creating more opportunities to use waste productively will help meet the growing global demand for agricultural products, generate

Cropland	30 million acres
Irrigation Water	4.2 trillion gallons
Pesticide	780 million pounds
Fertilizer (Nitrogen, Phosphorus, Potash)	5.6 billion pounds

Fig. 2.9 Agricultural inputs and resources used to produce food waste in the United States, annual average, 2007–2014. (Source: Conrad et al. (2018))

Box 2.7 Cutting Food Loss Improves Nutrition Too!
In Nigeria, nearly 30% of children under the age of 5 are vitamin A deficient, a condition that can lead to blindness and increased risk of disease and premature death (Maziya-Dixon et al. 2006). Tomatoes are an excellent source of vitamin A, and Nigerian farmers produced 1.8 million metric tons of tomatoes in 2010, making their country the 16th largest producer in the world (Ugonna et al. 2015).

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But the tomato supply chain is poorly organized and underdeveloped, and as a result half of the annual tomato harvest never reaches the market. Meanwhile, Nigeria imported 150,000 metric tons of processed tomato products in 2014, valued at $160 million (Ugonna et al. 2015).

The Geneva-based *Global Alliance for Improved Nutrition (GAIN)* has convened a coalition to develop solutions for reducing tomato losses that are market-based, nutritionally focused, locally adaptable, and financially sustainable. The *Postharvest Loss Alliance for Nutrition (PLAN)* brings leaders from government, finance, and academia together with representatives from Nigeria's tomato industry, including aggregators, processors, packagers, and cold chain operators.

The Alliance is targeting specific elements in the supply chain for improvement: crating and cooling technologies to protect prevent spoilage; a larger more reliable fleet of transport vehicles; new processing technologies and financing models to increase capacity; and outgrower schemes to link processors with farmers. Growers, traders, and processors also need technical assistance in negotiating contracts, tracking inventories, re-tooling and maintaining machinery, food safety protocols, and networking within the industry. Businesses with the capacity to scale up and innovate are receiving technical assistance and access to grants or affordable financing so that they can experiment with technologies and implement new approaches.

Strengthening the tomato value chain will not only give Nigerian producers access to a robust and growing market, but it will also provide low-income consumers a safe, affordable source of nutritious food that will improve the health of millions of children.

clean energy, mitigate carbon emission, create new jobs and industries, and improve incomes and food security, especially for small-scale producers.

2.8 Sustainable Agriculture Is Built on Productivity

Sustainable agriculture must satisfy human needs, enhance environmental quality and the natural resource base, sustain the economic vitality of food and agriculture systems, and improve the quality of life for farmers, ranchers, forest managers, fishers, agricultural workers, and society as a whole.[1] Improving agricultural sustainability requires multi-faceted, collaborative solutions involving producers, agribusinesses, transporters, retailers, and policymakers.

[1] Based on the definition in *Toward Sustainable Agriculture Systems in the twenty-first Century*, National Research Council, USA, 2010.

The United Nations defines sustainable growth as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." No one understands this delicate balancing act better than farmers, ranchers, forest managers, and fishers.

As they balance the demands of the present with the needs of the future, producers decide how much risk they are willing to take. They must consider the risk management options available to them, as well as factors they cannot control like weather, market prices, and economic or political uncertainty. While trade-offs are inevitable, policies and investments that support agricultural productivity and expand risk management capacity give producers the best chance to meet current and future needs while increasing their adaptability and resilience.

The next section of the chapter outlines how farmers in Colombia, the United States, Kenya, and India are adopting innovation to build productive sustainable agriculture systems.

2.8.1 Making Colombia's Beef More Sustainable

With abundant natural resources and increased political and economic stability in many countries, the Latin America and the Caribbean region (LAC) looks to agriculture as a key opportunity to feed its expanding middle class and become a breadbasket to the world. Agricultural productivity growth on the continent has skyrocketed in recent decades, and the region is now beginning to shift toward lower-carbon, environmentally friendly agriculture systems (Truitt Nakata and Zeigler 2014).

Despite this progress, difficult issues must be addressed. Conserving forests and biodiversity while improving livestock productivity in Latin America will be key to cultivating a successful sustainable agriculture system. While Latin America produces more beef than any other region, emissions from beef production are the second highest in the world after South Asia. Nearly one-third of Latin America's beef sector emissions come from land-use change for pasture expansion (Gerber et al. 2013).

The problem is acute in Colombia, one of the world's top cattle-producing countries with 23 million head of beef and dairy cattle. Cattle production uses 28% of Colombia's total land area (Nelson and Durschinger 2015), with 80% of all agricultural land in Colombia used for pasture.[2] Decades of civil conflict have exacerbated forest and biodiversity loses, with some three million hectares (7.4 million acres) of forest destroyed.

Colombia faces a challenge in helping its small- and medium-scale farmers shift to sustainable lower-carbon cattle production systems that use less land, conserve more forests, and provide higher incomes.

In the recent decade, many Colombian ranchers have begun to work with local cattle trade associations and the national Colombian Cattle Ranching Association

[2] Government of Colombia, Census of Agriculture (2014).

(Federación Colombiano de Ganaderos, FEDEGAN) as well as a Colombia sustainable livestock foundation (La Fundación Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria, CIPAV) to implement a more resilient form of livestock production: the silvopastoral production system (SPS) (Box 2.8).

Rows of fodder shrubs interspersed with grasses and trees characterize silvopastoral systems.

Photo credit: Neil Palmer, CIAT

With technical advice from CIPAV's SPS experts, ranchers plant fodder shrubs in high densities and intercropped with grasses and trees in rows. Using special fodder shrubs like *Leucaena leucocephala* and grasses like *Brachiaria* (high-protein fodder and grasses developed by CGIAR (Consultative Group for International Agricultural Research) institutions such as the International Center for Tropical Agriculture (CIAT)) boosts forage nutrition for cattle, allowing them to gain weight and produce more milk and meat in less time.

Leucaena shrubs grow rapidly and help fix nitrogen to soil, enriching soil health. Such forages grow deep root systems that help prevent soil erosion and can be integrated in other silvopastoral systems globally.

Box 2.8 Enabling Higher Productivity While Protecting the Environment in Colombia

Using a *healthy agricultural systems (HAS)* approach that focuses on increasing productivity while preserving the assets – the water, soil, and rich biodiversity that make productivity possible – *The Nature Conservancy (TNC)* and its partners are enabling farmers of all sizes to adopt practices that repair the land and sequester carbon, thereby ensuring more productive and profitable farm operations.

In Colombia, TNC and partners have supported 2600 ranchers in their transition to healthy agricultural systems over the past 7 years. Results have been impressive. Milk and meat production increased by 20%. Bird species numbers increased from 140 to 193, and the number of terrestrial mollusks,

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ants, butterflies, and other wildlife increased. Monitoring studies have confirmed reduced pollution of water sources.

Healthy agricultural systems in Colombia optimize natural ecosystems to restore vitality to landscapes, increase productivity and farm profit, slow deforestation, and boost sustainability.

Photo credit: Ganadería Colombiana Sostenible

The climate impact of the healthy agricultural systems approach is equally impressive. To date, farmers have contributed to capture 1.5 million tons of CO_2 equivalent by converting degraded pastures into silvopastoral systems (grazing systems incorporating special fodder, grasses, and trees with rotational plots for livestock). They have avoided additional emissions by planting secondary forests and by preserving the natural forests within the project areas. Both contributions are highly significant for Colombia, as the country's climate change commitment for the cattle ranching sector is to mitigate 10.3 million tons of CO_2 equivalent by 2030.

The Nature Conservancy is working to expand these practices across Colombia and other countries in Latin America, demonstrating that agriculture and natural habitat can work hand in hand to preserve the planet while increasing production to feed a growing world.

Trees provide shade for the cattle, protecting them from heat. And with more vegetation in the pastures, the soil retains nutrients, water, and carbon, making ranches more resilient to cyclical drought.

The Government of Colombia has proposed reducing the total land used for livestock by 21% by 2030, and the national cattle ranching association, FEDEGÁN, proposes similar pastureland reduction goals along with productivity increases. But making the transition from extensive cattle ranching systems to the newer silvopastoral systems is not easy, as it requires both technical support and a change in mindset. Many ranchers perceive forestry and cattle ranching as incompatible practices and often clear forested areas so cattle can graze on grasslands. Ranchers also fear that by using less pasture and conserving more forests, they risk losing some of their farmland to the government or other ranchers.

Government policy can help ranchers shift to silvopastoral systems with less risk. In Colombia, the Ministry of Agriculture and Rural Development is implementing more opportunity for ranchers to formalize ownership of land through secure land titling and helping ranchers to gain greater access to finance, as well as to certify they did not gain land through deforestation. Pilot programs are now available that provide low-interest loans and technical assistance to ranchers who want to convert their operations to silvopastoral systems. Eventually, more retail chains may be incentivized to purchase zero-deforestation beef, similar to retail agreements in Colombia with coffee growers.

By focusing on reducing costs, by providing quality meat and milk, and by certifying zero-deforestation branded meat and milk, Colombia's ranchers may be able to compete with imported products for the rising number of middle-class consumers. Implementing silvopastoral systems is an example of how innovation and productivity benefit farmers, consumers, and the environment.

2.8.2 How Innovation Grows More Sustainable Pork in the United States

Decades of public research and development along with research and growing partnerships with the private sector have resulted in high levels of pork productivity in the United States. Today is only takes five breeding hogs to produce the same amount of pork from eight hogs in 1959, or 38% fewer breeding animals.[3] As recently as 1989, the United States was a net importer of pork; today it is a net exporter, reaching more than 100 countries.[4] Consumers in these markets trust the safety and quality of US pork products, and demand continues to grow.

This substantial increase in pork productivity demonstrates how TFP works and the economic and environmental benefits of productivity growth.

Widespread adoption of innovative technologies and practices has increased pork output using the same amount or less land, labor, fertilizer, feed, machinery, and livestock. Efficient uses of these inputs generated cost savings for producers and consumers and improvements in the environmental footprint of the pork and animal feed value chains.

Pork productivity begins in the genes. Genetic researchers and veterinarians analyzed hundreds of animal traits to select and mate pigs to breed descendants that are healthier, use less feed, and produce more meat. Heritage breeds are cross-bred to create the best meat flavor and quality for consumers.

The pork feed value chain has also experienced a dramatic increase in productivity and sustainability (Box 2.9). Over the past 30 years, productivity-enhancing crop technologies and practices reduced the amount of land, labor, machinery hours,

[3] https://www.pork.org/wp-content/uploads/2012/06/10-174-Boyd-Camco-final-5-22-12.pdf

[4] https://www.ers.usda.gov/webdocs/charts/83729/usporkexports1.png?v=42887

Box 2.9 Building Sustainability Through the Pork Value Chain in the United States

Private sector investment, innovation, and scale are helping more farmers and ranchers shift to lower-carbon production systems. Smithfield Foods, the world's largest pig producer and pork processor, led the protein industry as the first to announce an ambitious greenhouse gas (GHG) emission reduction goal throughout its entire supply chain (*The 25 by '25 Initiative*). By 2025, Smithfield will reduce its absolute GHG emissions from its 2010 baseline by 25%, or four million metric tons, equivalent to removing 900,000 cars from the road.

The initiative began with the creation of a robust model to estimate the GHG footprint of Smithfield's entire supply chain – a collaboration with the University of Minnesota's NorthStar Institute for Sustainable Enterprise and in partnership with the Environmental Defense Fund (EDF). To ensure Smithfield reaches this goal, the company launched Smithfield Renewables, a platform within the organization that will unify, lead, and accelerate its carbon reduction and renewable energy efforts.

Smithfield made commitments to improve the carbon footprint of the feed crops for their pork production, optimize fertilizer use and improve soil health, install efficient manure management technologies, and more efficiently track and manage logistics of transportation fleets to cuts costs and emissions.

In 2017, Smithfield fed its pigs more than 7.4 million pounds of grain. The GHG analysis of the Smithfield supply chain noted that animal feed accounts for 15–20% of their entire production carbon emissions. By helping farmers in their feed supply chain shift to efficient fertilizer and soil health practices (such as using cover crops, nitrogen sensors, and other conservation practices) and by promoting sustainable grains such as sorghum (a resilient crop that costs less to grow, offers good nutrition for pigs, and serves as part of a crop-diversification strategy), the program provides a triple win: more profit for farmers, improved soil and water health with less greenhouse gas emissions for the planet, and nutritious sources of feed for healthy pigs.

fuel, and fertilizer used to produce hog feed. Alfalfa, corn, and soybean seeds improved through biotechnology and conventional breeding become healthy crops that are pest-resistant and herbicide-tolerant. Best practices for fertilizer management ensure that the right amount of the appropriate fertilizer is used at the right time and in the right place.

Machinery equipped with precision systems, such as GPS, cover every inch of the field with precisely planted seeds and treat each plant with the nutrients and crop protection products needed. Precision systems also allow less productive land to be identified and set aside for conservation use, such as pollinator or wildlife habitat.

These crops are blended with nutrients to make pig feed that is healthier and easier to digest, resulting in fewer methane emissions during the digestive process. “Smart barns” provide consistent temperature, comfortable housing, and readily available feed and water. With detailed data on the health and development of the herd, farmers can reduce energy use, save labor, and protect pigs from disease.

2.8.3 Investing in Productivity for Africa’s Dairy Hub: Kenya

Kenya’s dairy farmers produce more than five billion tons of milk per year, the most in Africa (FAOSTAT 2017). The dairy industry accounts for 6 to 8% of Kenya’s GDP and provides income for two million households. Consumers also benefit from Kenya’s dairy productivity; per capita milk consumption is 100 liters (26 gallons) per year, more than any other developing country (Katothya 2017).

Kenya’s dairy industry is endangered by climate change. A substantial increase in mean temperature is predicted for East Africa and could lead to a reduction in fodder output and grazing land capacity. Increasing temperatures threaten the health and productivity of livestock. As droughts lengthen and intensify, large-scale cattle losses are likely. Small-scale farmers will be forced to sell cows or land to cope with the loss of income, making it difficult for them to recover financially when the drought is over.

As part of its climate change adaption and mitigation strategy, Kenya’s dairy sector needs to increase the productivity of its dairy cattle and reduce the GHG emission intensity of milk production (Box 2.10). Sub-Saharan Africa’s milk production has the highest emission intensity in the world, three times greater than the global average and almost double that of South Asia.

Kenya is home to 75% of the dairy cattle in Southern and Eastern Africa; 80% of Kenya’s milk output is produced by small-scale farmers. By improving cattle productivity and reducing emission intensity, the dairy sector in Kenya can significantly mitigate greenhouse gases while increasing small-scale farmer income.

More than half of the emission intensity of milk production in sub-Saharan Africa comes from methane produced during a cow’s digestive process. One strategy for reducing these emissions is to add legume silages to a cow’s diet. Legumes are digested more efficiently, so a cow produces less methane and more milk. Improving the genetics of dairy cattle is another way to reduce methane emissions

Box 2.10 Better Breeds and Better Feed Are Key for Climate Resilience

Photo credit: International Livestock Research Institute (ILRI)

The drylands of northeastern Kenya are particularly vulnerable to climate change. This region receives less than 500 millimeters (20 inches) of rain per year and has fewer than 90 plant growth days. Many of the people in this region are pastoralists, moving regularly to find forage for their livestock.

Boran cattle are well-suited to the dryland areas of East Africa but produce very little milk and meat compared to cross-bred and high-grade varieties. The International Livestock Research Institute (ILRI) farm in Nairobi is breeding Boran cattle that efficiently digest the low-quality grasses and silages that are common to the drylands. This will decrease methane emissions and improve milk and meat productivity.

In addition to improved cattle genetics, improving the fodder and feed for cattle is key to achieving more robust milk products and livestock that are climate-resilient. The International Center for Tropical Agriculture (CIAT) has developed *Brachiaria* grass varieties that are drought-resistant and increase milk productivity in dairy cows by 40%.


Photo credit: Georgina Smith/CIAT

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These nutritious grasses are easier for cattle to digest. Demand for these improved grasses is skyrocketing, and farmers are now diversifying their income by growing and selling them at the local "fodder stores" which purchase and sell fodder in local markets.

and increase milk productivity. Kenya has already made strides in this direction; the country is home to more than 70% of the cross-bred and high-grade dairy cows in Africa. Sixty percent of the milk produced in Kenya (three billion liters) comes from high-grade cattle and cross-breeds. But high-grade dairy cattle are more susceptible to disease than local cattle varieties, so breeding for disease resistance is a top priority.

The health of cattle in Kenya and exposure to disease continue to threaten productivity and farmer livelihoods. Part of the county is infested with tsetse fly, the biological vector of trypanosomiasis (sometimes called sleeping sickness), a parasitical disease that causes anemia and emaciation in cattle. The condition is chronic, and if left untreated, it is often fatal. If a cow survives the infection, its milk productivity can drop by 30 to 40%. Trypanosomiasis is a zoonotic disease that is passed between animals and humans via the tsetse fly, although the number of human cases in Africa has dropped substantially due to sustained public health efforts.

To ensure a sustainable livelihood and earn sufficient incomes to invest for the future, small-scale dairy farmers need consistently healthy, productive herds. Good animal care and feeding practices promote productivity and prevent disease, but access to affordable, quality animal healthcare products is also essential.

2.8.4 Mechanizing for the Future in India

India's small-scale farms have enjoyed healthy yields, thanks to the Green Revolution and continued improvements in seeds, crop protection products, and access to fertilizers (Box 2.11). Nevertheless, labor productivity on small farms remains stubbornly low. Family members do the bulk of the farm work because mechanization rental and ownership are more expensive than family or hired labor.

Not only is this an inefficient use of labor, but it contributes to high rates of rural poverty and food insecurity. For example, the income from a one-hectare farm, even if it is high-yielding, must meet the needs of as many as 12 people. As a result, small farmers are heavily dependent on food rations, wage labor, and government support to supplement their farming incomes.

Custom Hiring Centers (CHCs) give farmers affordable access to mechanization without having to own the machines themselves. Farmers can rent tractors and implements for soil preparation, seeding, application of nutrients, and crop protection and harvesting. CHCs are centrally located to serve several villages, reducing

Box 2.11 Balanced Crop Nutrition Boosts Productivity and Incomes in India

Since 2008, the *Mosaic Villages Project*, a collaboration between The Mosaic Company, The *Mosaic Company Foundation,* and implementing partner, the *S M Sehgal Foundation*, has helped Indian farmers move out of poverty and achieve greater food security. Mosaic's investment includes funding and the expertise of Mosaic agronomists who work alongside local partners to train farmers in balanced crop nutrition and agronomic best practices.

Photo credit: The Mosaic Company Foundation

In the remote districts of Mewat and Alwar in Rajasthan, the *Krishi Jyoti Project*, or "enlightened agriculture," helps farmers improve productivity of three crops: pearl millet, wheat, and mustard. The project focuses on five key aspects of agricultural production: soil health, seed and fertilizer, water management, agronomic training, and market linkages. Village leaders selected farmers representing all castes and landholding sizes to participate in the program.

With balanced crop nutrition practices – using the right mix of macro- and micro-nutrients to meet the needs of the crops and soils – together with agronomic expertise and financial support, farmers increased yields by as much as 25% over traditional farming practices. In total, Krishi Jyoti has directly benefited more than 26,000 farmers across 60 villages and boosted cultivation across nearly 16,000 acres of land. Average income per acre has also grown between 4480 Rs ($70 US) for wheat to 5760 Rs ($90 US) for mustard.

Communities participating in the Krishi Jyoti Project are using the additional income to help create a better life for future generations. The S M Sehgal Foundation and Mosaic funded renovations for 20 schools in Alwar, Mewat, and Sonipat – including adding sanitation facilities, safe drinking water systems, and school kitchens.

the time and cost of transporting the equipment. CHC partnerships include equipment manufacturers, such as *John Deere*, who provide the equipment, product service, and training in agronomy practices and equipment usage. State governments contribute financial support and invest in infrastructure for the centers and in road improvements to ensure that equipment can be transported efficiently. Local entrepreneurs are hired to operate the centers, deploy and maintain the equipment, as well as manage the contracts with the farmers.

Nearly 90% of farmers with less than two hectares participate in a government food ration program. India has 120 million individual landholdings under two hectares. To meet its targets for reducing food insecurity and poverty, the government needs to invest in non-agricultural employment and skills training for rural workers to move more people out of agriculture, particularly manual labor, while fostering off-farm agricultural employment in jobs such as agro-dealerships, equipment and machinery maintenance, processing, and storage.

Farmland consolidation can help achieve greater economies of scale as well. The necessity for consolidation is amplified by the growing competition for land. India's rapidly expanding manufacturing and service industries need room to grow and are already competing for land and displacing farmers across the country.

2.9 Policies to Create an Enabling Policy Environment for Productivity in Agriculture

Meeting the rising demand for nutritious, affordable food as well as materials for fuel, clothing, housing, and consumer products will require innovative, productive, and sustainable food and agriculture systems. Together, governments, producers, and the entire agri-food system must commit to improve and transform the system to achieve a healthy population and a healthy planet. Improving agricultural sustainability requires multi-faceted solutions built on science-based public policies.

Productivity in agriculture grows when governments invest in public research, development, and extension services; when all participants in the agri-food system embrace, customize, and disseminate science-based and information technologies; when the private sector can be incentivized to form partnerships for infrastructure development and improved nutrition; and when capacity for regional and global trade in agriculture is streamlined.

2.9.1 Smart Regulatory Systems Build Trust and Competitiveness for Productivity

Governments establish agricultural policies and regulations to ensure human health and safety, protect the environment and animal welfare, and foster economic growth while meeting consumer needs for food, fiber, fuel, and other coproducts. Smart regulatory systems that keep pace with rapidly changing innovations in science and technology can foster the adoption of such innovations (Box 2.12).

Box 2.12 A Twenty-First-Century Regulatory System for Agriculture
For thousands of years, agriculturalist have improved the quality and performance of crops and livestock through trial and error, saving seeds from plants or breeding animals from those that exhibited the desired traits. Today, the tools used by agricultural breeders have evolved through science-based innovations. With an ability to understand the genetic sequence of plants and to link a particular gene with a specific plant characteristic, breeders can quickly and efficiently improve plants while avoiding the transfer of unwanted genes.

In the past decade, *new gene-editing techniques such as CRISPR-Cas* (clustered regularly interspaced short palindromic repeats, DNA sequences that can be used to instruct genes to perform beneficial functions and more precisely edit DNA) have become available, unlocking potential benefits for farmers, consumers, and the environment. Breeders can now edit genes by turning on or off various genetic functions that increase crop yields during drought, protect the plant or crop against viruses and pests (reducing the amount of pesticide needed), improve the nutritional quality and content of crops, or help vegetables maintain longer shelf life. Gene-editing technologies such as CRISPR-Cas rely on natural processes that happen in the genome but channel and target those changes more precisely.

Seed companies are exploring how this technology allows breeders to develop better hybrids by quickly finding and leveraging the inherent diversity existing in crops. Livestock breeders are also harnessing the power of gene-editing tools to improve the resilience, productivity, and nutritional content of animals for better meat, milk, and eggs.

To fight a devastating corn disease affecting small-scale farmers in Africa (maize lethal necrosis), Corteva Agrisciences™ and the *International Maize and Wheat Improvement Center (CIMMYT)* have formed a public-private research partnership to improve the resilience of maize to this devastating disease using CRISPR-Cas technology.

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Plants and animals derived from new breeding methods such as biotechnology and gene-editing should be assessed for potential health or safety impacts, rather than for the processes used to produce the trait or product. Without streamlined modern regulatory systems, innovation from small companies, public-private research partnerships and universities many not reach farmers who need solutions. In the United States, the regulatory system for biotechnology had not been revised since 1986 and required modernization to address new breeding technology. In 2020, the USDA finalized new regulations under the Sustainable, Ecological, Consistent, Uniform, Responsible, Efficient (SECURE) rule, providing new guidance for plant breeding innovation.

Plant breeding innovations like CRISPR-Cas will only be achieved through improving and updating regulatory systems and active engagement and collaboration with farmers, academia, governments, NGOs, and public research institutes, both in the United States and around the world.

A successful regulatory system establishes predictable, clear, science-based operating conditions for farmers and ranchers – particularly with regard to seeds, crop protection, and animal health – as well as for mechanization companies, insurance and finance firms, and food processing and retail industries, so that the overall agriculture sector can deliver value for people, the environment, and the national economy.

In today's global competitive environment, regulatory systems are being called upon to do even more, as consumers seek more information about production methods, nutritional content, labor practices, and sustainability of local, national, and international food and agriculture systems. Transparency and traceability are growing in importance for developing consumer trust, while affordability and accessibility remains a paramount concern for many customers.

It is especially important that government regulatory systems help foster productivity and innovation while avoiding unnecessary costs, delays, and burdens to the agriculture sector, ultimately impacting the ability to swiftly deliver quality products to consumers. Regulatory systems should have a sound legal and empirical basis, minimize costs and market distortions, and promote innovation through intellectual property protection and market incentives. They must be clear and practical for users and be compatible with domestic and international trade principles.[5] Smart regulatory systems contribute to innovation and productivity when all the participants – government, industry, producers, scientific researchers, members of the media, and consumers – responsibly engage in practice as well as understanding about new opportunities that science and technology bring (Fig. 2.10).

Ideally, farmers practice good stewardship with innovation technology; input providers, processors, and retailers work within regulatory frameworks; government consults with all relevant parties and establishes well-functioning, science-

[5] https://www.oecd.org/fr/reformereg/34976533.pdf

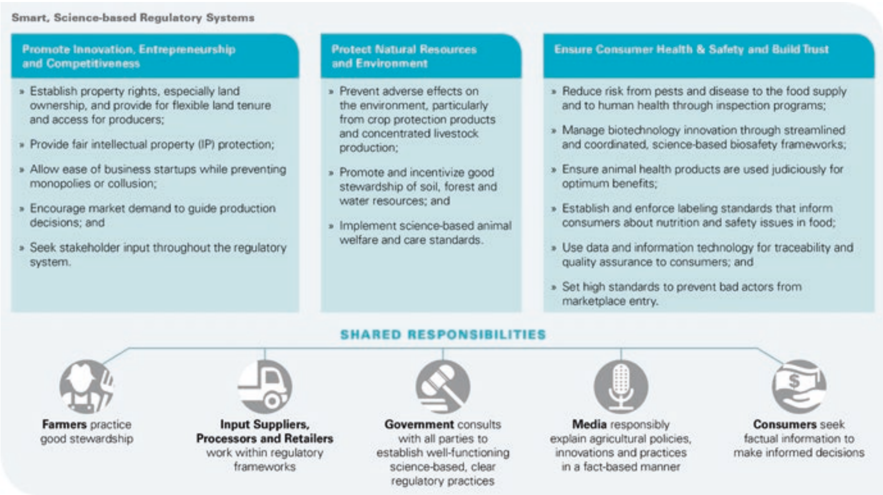

Fig. 2.10 Science-based regulatory systems for productivity in agriculture. (Source: 2016 Global Agricultural Productivity Report (GAP Report))

based, and clear regulatory practices; media responsibly explain agricultural policies, innovations, and practices in a fact-based manner; and consumers have easy access to facts to make informed decisions.

2.10 Investing in Farmers

To maximize the productive potential of investments in agricultural R&D, innovations such as mechanization and improved practices for soil and animal health, governments, and the private sector need to invest in the productivity of farmers, ranchers, foresters, and fishers.

Farmers and producers are already the largest investors in the agricultural value chain. A review of agricultural investment sources in low- and middle-income countries by the *UN Food and Agriculture Organization (FAO)* found that 78% of agriculture investments come from on-farm investment in agricultural capital by farmers themselves (Lowder et al. 2012) The remaining 22% comes from government expenditures, public sector agriculture R&D, foreign direct investment, and official development assistance.

Yet, millions of small-scale farmers, especially women and young people, are undercapitalized because they do not have legal title to their most important capital asset, their land.

In low-income countries, the right to occupy, cultivate, inherit, lease, buy, or sell land is often determined by a complex system of social customs that are granted and arbitrated by communal authorities (sometimes called "customary" or "tribal" authorities). Communal rights may be recognized by civil authorities as well, but they do not have the same legal standing as land titles or leaseholds granted by the state (Cousins 2016). Formal lenders see communal tenure rights as a risky investment and are reluctant to extend credit, regardless of the productive potential of the land.

Communal tenure systems are often dominated by social and patriarchal hierarchies that disenfranchise vulnerable groups. As a result, gender, age, and community standing often determine the quality, quantity, and terms of the landholdings.

Furthermore, without civil legal protections, communal landholders have little recourse if their land is appropriated by customary or state authorities. In these circumstances, communal landholders, particularly women, are less likely to make investments in improved seeds or fertilizer, suppressing their earning potential and making it difficult to save for capital purchases, such as mechanization and irrigation technologies. Likewise, long-standing and widespread land disputes stifle the sale, purchase, leasing, and inheritance of land, effectively freezing the land market, discouraging productive investment, and stifling economic growth (Valetta 2012).

Policies that secure and promote farmer access to land, water, and improved inputs enable farmers of all scales to remain competitive even during the challenging phases of business cycles and help them respond to changing climate patterns.

2.11 Concluding Remarks

Without productivity growth, the world's agriculture and food systems will not be able to sustainably produce the food, feed, fiber, and biofuel needed for ten billion people in 2050. An enabling policy environment also supports the productive potential of farmers, ranchers, foresters, and fishers by generating new market opportunities, increasing their access to affordable financing, and improving the environmental sustainability of their operations. The data show that a global focus on productivity growth is urgently needed to reverse the downward trend in productivity growth.

While this chapter has focused on the role of the producer, the role of the consumer in productive sustainable food systems is just as critical. Significant reductions in food waste are critical to sustainable food systems, and most food waste occurs at the retail and consumer point of the value chain. Consumers also need to educate themselves on the science and practice of agriculture and be willing to challenge their assumptions about what makes their food "sustainable." Without consumer acceptance of science-based innovations such as biotechnology, gene-editing, and proven practices in livestock husbandry, the target levels for agricultural productivity and sustainability will not be realized.

Innovation and productivity are interdependent, but access to and acceptance of innovative technologies and practices must be improved if they are to realize their potential.

References

Conrad Z, Niles MT, Neher DA, Roy ED, Tichenor NE, Jahns L (2018) Relationship between food waste, diet quality, and environmental sustainability. PLoS One 13(4):e0195405. https://doi.org/10.1371/journal.pone.0195405

Cousins B (2016) Land reform in South Africa is sinking. Can it be saved? Thought piece commissioned by Nelson Mandela Foundation, Council for the Advancement of the South African Constitution, and Hans Seidel Foundation, https://www.nelsonmandela.org/uploads/files/Land__law_and_leadership_-_paper_2.pdf

Daidone S, Davis B, Dewbre J et al. (2014) Zambia's Child Grant Programme: 24-month impact report on productive activities and labour allocation, FAO. http://www.fao.org/3/a-i3692e.pdf

FAOSTAT on line (2014). http://www.fao.org/faostat/en/#home

FAOSTAT on line (2017). http://www.fao.org/faostat/en/#home

Fuglie K (2018) R&D capital, R&D spillovers, and productivity growth in world agriculture. Appl Econ Perspect Policy 40(3):421–444

Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A, Tempio G (2013) Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome

Hunter CM, Smith RG, Schipanski ME, Atwood LW, Mortensen DA (2017) Agriculture in 2050: recalibrating targets for sustainable intensification. Bioscience 67(4):386–391

Katothya G (2017) Gender assessment of dairy value chains: evidence from Kenya, Rome, FAO

Landes M et al. 2017. India's dairy sector: structure, performance and prospects, USDA Economic Research Service (USDA ERS), LDPM-272-01

Lowder SK, Carisma B, Skoet J (2012) Who invests in agriculture and how much. FAO, EAS Working Paper No. 12-09

Maziya-Dixon B, Akinyele IO, Sanusi RA, Oguntona TE, Nokoe SK, Harris EW (2006) Vitamin A deficiency is prevalent in children less than 5 y of age in Nigeria. J Nutr 136(8):2255–2261. https://doi.org/10.1093/jn/136.8.2255

Naresh RK et al (2017) Climate change and challenges of water and food security for smallholder farmers of Uttar Pradesh and mitigation through carbon sequestration in agricultural lands: an overview. Int J Chem Stud 5(2):221–236

Nelson N, Durschinger L (2015) Supporting zero-deforestation cattle in Colombia. USAID-supported Forest Carbon, Markets and Communities Program. Washington

OECD/FAO (2016) OECD-FAO agricultural outlook 2017–2026. OECD Publishing, Paris. https://doi.org/10.1787/agr_outlook-2016-en

OECD/FAO (2017) OECD-FAO agricultural outlook 2017–2026. OECD Publishing, Paris. https://doi.org/10.1787/agr_outlook-2017-en

Regúnaga M (ed) (2013) Global food security and agricultural natural resources: role and views of Argentina, Brazil, Paraguay and Uruguay, 1a edn. Editorial De Yeug, Argentina, 160 p

Steensland A, Zeigler M (2018) Global agricultural productivity report® (GAP Report®). Global Harvest Initiative, Washington, D.C.

Truitt Nakata G, Zeigler M (2014) The next global breadbasket: how Latin America can feed the world. Inter-American Development Bank and the Global Harvest Initiative. https://publications.iadb.org/en/publication/17428/next-global-breadbasket-how-latin-america-can-feed-world-call-action-addressing

Ugonna C, Jolaoso MA, Onwualu PA (2015) Tomato value chain in Nigeria: issues, challenges and strategies. J Sci Res Rep 7(7):501–515. https://doi.org/10.9734/JSRR/2015/16921

Valetta W (2012) Rural land tenure security and food supply in southern Benin. In: Knowledge and innovation network, Volume II, Issue I, Spring/Winter 2012–2013.

von Lampe M et al (2014) Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agric Econ 45(1):3–20

Zeigler M, Steensland A (2017) Global agricultural productivity report® (GAP Report®). Global Harvest initiative, Washington, D.C.