UNLOCKING INNOVATION

ASSESSING THE ROLE OF AGRICULTURAL R&D IN LATIN AMERICA AND THE CARIBBEAN

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF BOXES

LIST OF TABLES

EXECUTIVE SUMMARY

This report presents a comprehensive analysis of public agricultural research and development (R&D) in Latin America and the Caribbean (LAC), focusing on the contextual factors influencing agricultural R&D investment and their implications for agricultural productivity growth.

The analysis combines new data for ten LAC countries collected by the International Food Policy Research Institute's (IFPRI's) Agricultural Science and Technology Indicators (ASTI) program with support from the Inter-American Development Bank (IDB), with existing ASTI and other datasets. By integrating these various datasets, the report provides an in-depth examination of recent trends in public agricultural research spending, capacity, and outputs across the LAC region.

The findings reveal a historical underinvestment in agricultural R&D in LAC, with a disproportionate concentration of resources in a few countries, notably Brazil. While some countries have witnessed increased public agricultural R&D spending in recent years, a significant portion of this growth relies on external funding from donors and development banks, raising concerns about long-term sustainability. Furthermore, the report highlights the pressing issue of inadequate human capital in agricultural research within many LAC countries, underscoring the low priority given to agricultural R&D. This neglect leads to a gradual depletion of the critical human resources necessary for research, with potential consequences that could take decades to rectify. Moreover, countries with smaller agricultural research systems face additional challenges, including underdeveloped innovation environments, lower quality and development of education and scientific research systems, and reduced effectiveness of their R&D efforts.

Despite the demonstrated high returns on agricultural R&D investments, LAC countries continue to lag in allocating sufficient resources to this critical area. The traditional agricultural research model faces major challenges in keeping pace with the evolving agricultural landscape and food system more broadly. Consequently, its impact has been limited, leading to reduced political significance and financial support. To address these issues and maximize research impact, this report recommends integrating research institutions into national science and innovation systems that are aligned with the evolving food value chain. It also highlights the importance of fostering alliances between countries, addressing regulatory gaps, enhancing human and institutional capacities, and establishing flexible funding systems.

These recommendations are part of a long-term agenda for structural change. Aligning research systems with the changing dynamics of the food system will be crucial for overcoming future growth challenges and promoting sustainable development in the region.

/1/ INTRODUCTION

The world is currently facing multiple challenges that have brought agriculture to the forefront. Four significant converging trends are driving this direction. Firstly, feeding an estimated 9.7 billion people by 2050, which requires a 70 percent increase over current agricultural production levels, remains a major challenge (United Nations Population Division, 2022). Secondly, there is clear evidence of a deterioration in the natural resource base, and projections on the effects of climate change emphasize the need to adjust agricultural production patterns to reduce the negative impact of current actions and adapt to new climate parameters (Pörtner et al., 2022).

Thirdly, agriculture is no longer a stand-alone sector, but rather part of a globalized food system with integrated value chains that have undergone significant institutional and technological changes (de Janvry, 2010). This has resulted in a structural shift in agricultural growth, propelled by urbanization and changes in demand. This shift has led to the emergence of economies of specialization in the midstream and downstream segments of the value chain, increasing the significance of post-farmgate segments while decreasing the share of farmers in the total value added of the chain.

Finally, a research paradigm is emerging that challenges the traditional distinction between basic and applied science due to the latest advancements in biotechnology and informatics. As Trigo et al. (2013) warned ten years ago, this paradigm shift has profound implications for research institutions, and will demand more collaborative relationships between research institutions, universities, and the private sector.

All these simultaneous developments have significant implications for agricultural research. The innovation process is evolving, with product diversification and differentiation becoming increasingly important competitive instruments. Technological advancements are no longer solely focused on higher yields, productivity, and cost reduction, but also on quality, harvest opportunities, and the conservation or processing of products. Furthermore, there is a need for an integrated approach to primary agricultural production that includes processing and market stages to define technological strategies and research and development (R&D) priorities. A research strategy that isolates primary production from agribusiness, inputs, and processing, and from final distribution, will hinder the generation of innovations and improvements in competitiveness (Trigo et al., 2013).

Latin America and the Caribbean (LAC) is well-positioned to address the three converging challenges facing agriculture. The region boasts abundant land, water, and biodiversity resources that are crucial for the future. Furthermore, any forward-looking analysis of future supply and demand conditions highlights that LAC has a critical role to play in achieving global balances in food, energy, and the environment. However, to fully realize this potential, LAC must improve its technological strategies for sustainable intensification, better utilize biodiversity, genetically transform products to meet consumer demands, and efficiently use plants and animals post-harvest and in industrial settings. The question remains, are the agricultural research systems in LAC countries prepared to rise to the occasion?

The establishment of public research institutes in LAC in the late 1950s, aimed to accelerate agricultural productivity growth, increase food supply, and transfer labor to urban industrial sectors. To complement this institutional scheme, the International Centers for Agricultural Research were created from 1960 onwards, sponsored by the Consultative Group on International Agricultural Research (CGIAR), aimed to facilitate linkages between national institutions and centers of excellence in advanced countries. The International Maize and Wheat Improvement Center (CIMMYT) in Mexico, the International Center for Tropical Agriculture (CIAT) in Colombia, and the International Potato Center (CIP) in Peru were founded between 1966 and 1972 and have since become important actors in LAC's regional system of research and technology transfer.

Until the early 1980s, this institutional system effectively achieved its goals, particularly with regard to enhancing productivity and keeping food prices low for an increasingly urbanized population (Nin-Pratt et al., 2015). However, after the "lost decade" of the 1980s, LAC countries started overhauling their macroeconomic policy frameworks, as the import substitution industrialization model followed by most countries was blamed for the poor performance of the agricultural sector. The model discriminated against agriculture due to exchange rate overvaluation, export taxes, protection of the industrial sector, and direct market interventions. Policy changes brought about a new approach to rural development, which had implications for agricultural research. Programs by productive sectors or crop were replaced by a more comprehensive vision of poverty and rural development, in which technology was just one instrument of state intervention, occurring within a framework of broader programs and projects.

These changes have led to the portrayal of agricultural research systems as ineffective in fulfilling their mandates, which may be one of the reasons for the persistent underinvestment that has affected public research institutions in the region. The perception of low impact further fuels underinvestment, weakening existing capacities and negatively affecting results, creating a cycle. **The result is that the traditional research system led by the national agricultural research institutes (INIAs) loses weight in favor of new research institutions and organizations that favor learning, complementation, interaction, and multiplicity of actors, as elements in discussions on science, technology, and innovation policies, particularly for the agri-food sector** (Trigo et al., 2013). In recent years, new institutional developments are moving towards innovation systems: a network of agents and their interactions related to the adoption and diffusion of new products and technological processes in an economy. This shift recognizes that competitiveness is not only linked to science and technology but also to how they are effectively translated into innovations in specific economic and social processes. Therefore, assessing agricultural research in LAC requires looking at each country's innovation context, opportunities, and constraints, including infrastructure, education, and public and private investment in R&D. It also requires identifying the best institutional frameworks and most promising paths to use research resources effectively and increase innovation capacity.

To assess agricultural R&D systems in LAC, quantitative data are essential. They measure, monitor, and benchmark the inputs, outputs, and performance of agricultural R&D systems over time, and are an indispensable tool when it comes to assessing the contribution of agricultural R&D to agricultural productivity growth, and economic growth more generally. Such data are also crucial for research managers and policymakers in formulating agricultural research policy and making decisions about strategic planning, priority-setting, monitoring, and evaluation. For these reasons, the International Food Policy Research Institute's (IFPRI's) Agricultural Science and Technology Indicators (ASTI) program, with IDB support, collected comprehensive data from agricultural R&D agencies in government, higher education, and nonprofit sectors for the period 2017–2020 in ten predominantly Central American and Andean countries, including Belize, Bolivia, Costa Rica, the Dominican Republic, Ecuador, Guatemala, Honduras, Nicaragua, Panama, and Peru. This new data was merged with existing ASTI datasets for these countries and other countries in the region to provide a more comprehensive overview of the state and direction of agricultural R&D in LAC and its impact on the region's food systems.

The objective of this report is to present a comprehensive and detailed analysis of recent developments in agricultural research spending, capacity, and outputs in LAC. The report explores the various factors that influence the performance of agricultural research systems in the region and their correlation with a country's overall level of innovation capacity and food system development. The analysis is organized into three main parts to provide a structured approach. The first part offers an overview of the environment in which agricultural R&D occurs (Section 2) and examines recent trends in agricultural R&D spending across ten countries, using updated ASTI data (Section 3). The second part (Section 4) conducts a comparative analysis of research capacity and investment by drawing on both updated and historical data from the ASTI database to identify the strengths and weaknesses of agricultural research systems in the region. In the third part of the analysis (Section 5), the focus shifts to analyzing the connection between the performance of agricultural research systems and agricultural sector growth, identifying the contribution of public R&D investment and knowledge spillovers to production and productivity growth. The final discussion, presented in Section 6, consolidates the key findings derived from the analysis and explores the implications for agricultural research in LAC. Importantly, it concludes that many of the challenges identified by Trigo et al. in 2013 persist to this day, underscoring the continued relevance of their recommendations made a decade ago.

/2/

CONTEXT: INNOVATION CAPACITY AND THE FOOD SYSTEM

This section explores two crucial components that help to comprehend the factors that affect public agricultural R&D spending: a country's food system development and its innovation capacity. Quantifying these two factors provides useful insights into the broader implications for R&D systems, which will be discussed in further detail.

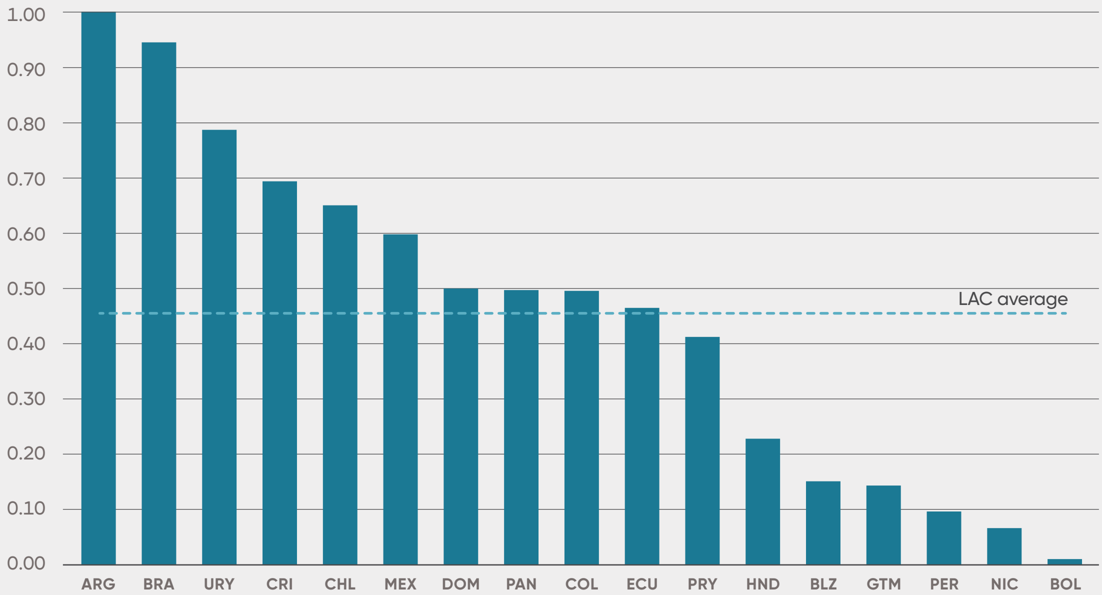
To evaluate the advancement and complexity of food systems in different countries, Nin-Pratt and Stads (2023) built a food system development index (FSDI) that measures the development of the system at the farm, post-farm, and consumption levels. At the farm level, it is assumed that capital intensity, the value of capital, and purchased inputs per worker (irrigation equipment, seeds, fertilizer, insecticides, herbicides, tractors and combines, and sprayers) are positively correlated to the adoption of improved technologies and integration of farmers with output and input markets, better access to financial markets, and to production services. The second sub-index quantifies the development of the post-farm segment of the food system and measures the length and reach of the value chain, the quality of local supply, industrial cluster development, product sophistication, the extent of marketing, and the presence of a formal grocery sector. A high value of the index represents more and stronger links between farmers, the post-farm segment, and the final consumers, more product differentiation, higher importance of product quality and food safety regulations. On the demand side, the index measures changes in diet diversity (proportion of staple food) and the consumption of animal protein, providing insights into a country's evolving dietary habits. For more detail on the FSDI, please consult **Annex A**.

Figure 1a illustrates significant disparities in food system development among LAC countries. Argentina, Brazil, Uruguay, Costa Rica, Chile, and Mexico have the most advanced food systems, while Honduras, Belize, Guatemala, Peru, Nicaragua, and Bolivia have the least developed ones. FSDI values for the Dominican Republic, Panama, Colombia, Ecuador, and Paraguay fall in between these two groups. Despite the overall similarities in the development of the value chain across LAC countries **(Figure 1b)**, differences in food system development are mainly attributed to differences in food demand and capital intensity in agriculture.

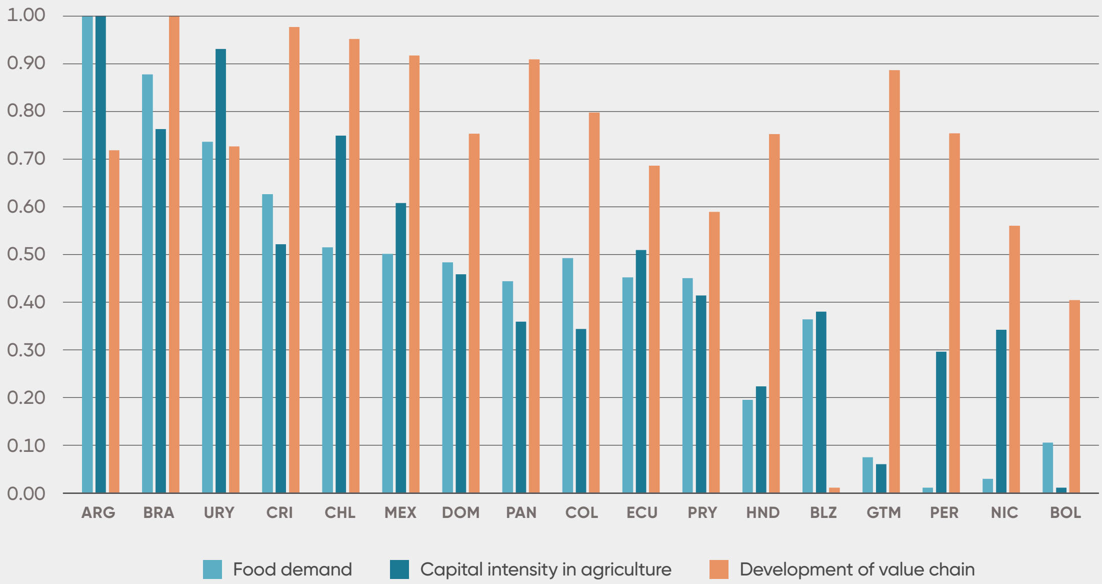
The innovation capacity index (ICI) developed by Nin-Pratt and Stads (2023) comprises four sub-indices. The first sub-index, education and human capital, evaluates enrollment at all levels of education. The second sub-index, research capacity, assesses a country's overall performance in science, including metrics such as the number of publications in various fields like engineering, computer science, biochemistry, genetics, and molecular biology, and the H-index, which is used to gauge the impact and performance of scholarly output. The third sub-index, innovation environment, evaluates the level of competition in local markets, development of financial services, access to credit, and investment in R&D and staff training. Finally, the fourth sub-index, quality of institutions, captures six broad dimensions of governance, including voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption. For more detailed information on the ICI and its sub-indices, please consult **Annex A**.

Figure 1. Food system development in Latin America and the Caribbean

1a. FSDI scores of LAC countries



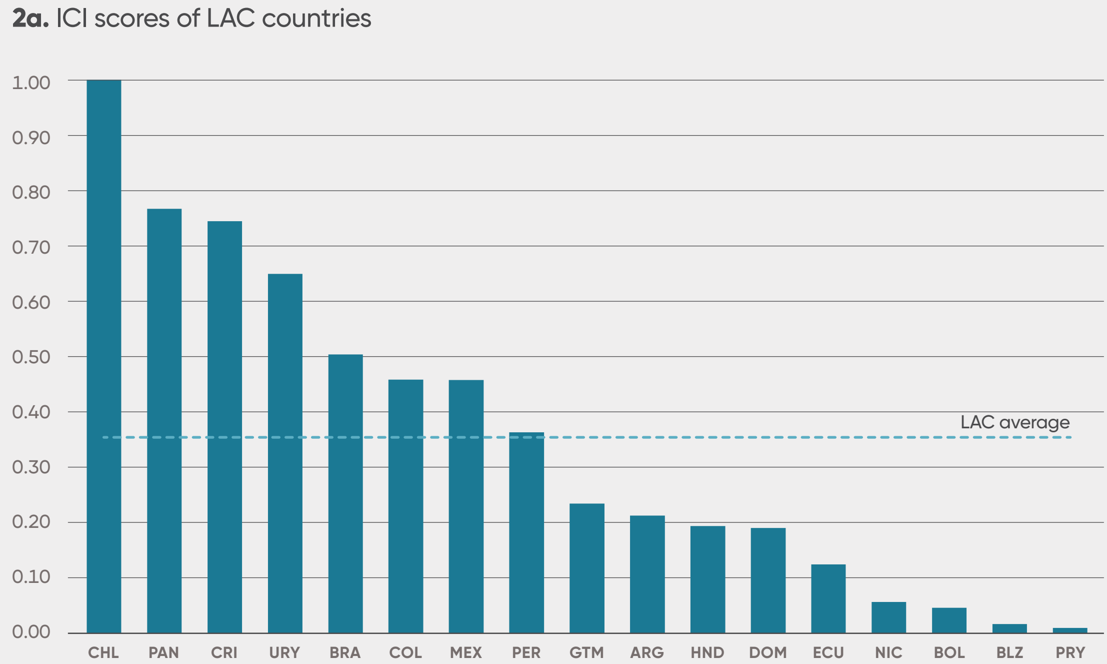
1b. Disaggregation of the FSDI



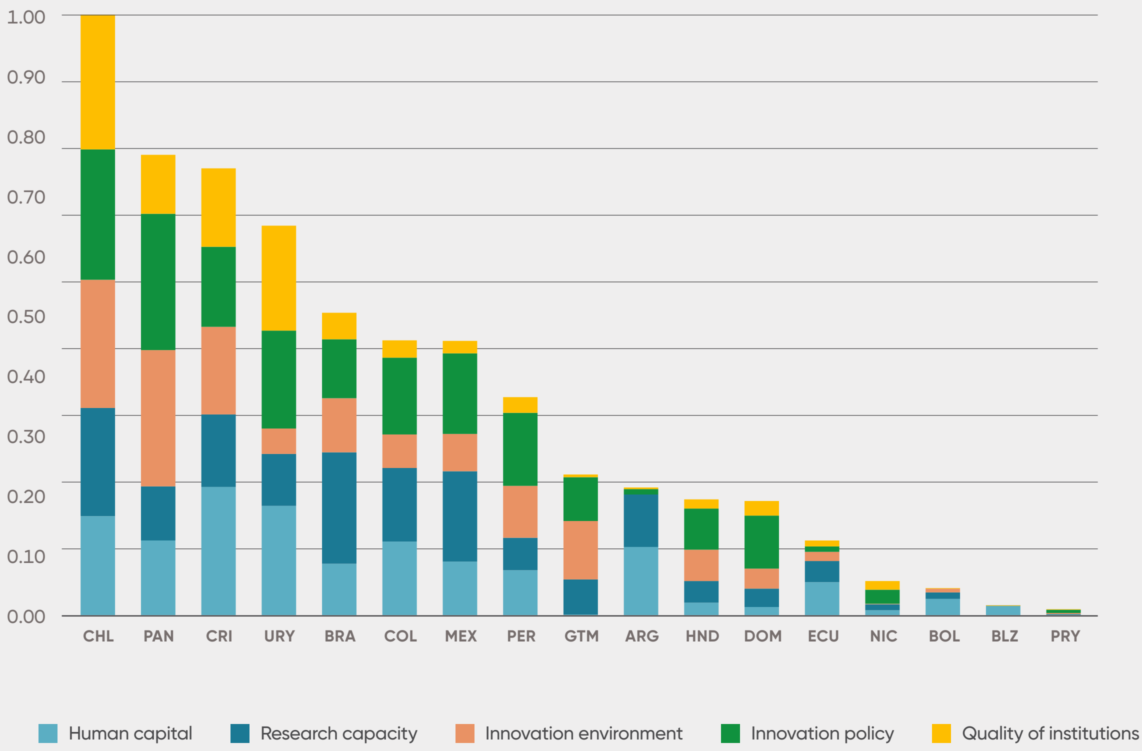
Sources: Elaborated by authors based on Schwab (2019), ASTI (2023), SCImago (2023), USDA-ERS (2023), and World Bank (2023).
Notes: For more detail on the FSDI, see Nin-Pratt and Stads (2023) and Annex A.

As shown in **Figure 2a**, the innovation capacity of different LAC countries varies considerably. Chile tops the ICI in the region, followed by three relatively small countries —Panama, Costa Rica, and Uruguay— with ICI values around 0.7. These four innovation leaders are followed by some of the region's largest economies —Brazil, Colombia, and Mexico— each scoring ICI values close to 0.5. On the other hand, Nicaragua, Bolivia, Belize, and Paraguay recorded the lowest ICI scores. Additionally, Guatemala, Honduras, Dominican Republic, and Ecuador all recorded ICI scores below the regional average of 0.35, with Argentina being an unexpected addition to this group. Further analysis of the disaggregated ICI indicates that countries with ICI scores above the regional average have higher levels of human capital and research capacity than those below the average **(Figure 2b)**. Disparities in the innovation environment, innovation policy, and institutional quality account for the differences between innovation leader Chile and other countries scoring above-average ICI values. These factors also explain the relatively lower rankings of Brazil and, particularly, Argentina.

Figure 2. Innovation capacity in Latin America and the Caribbean



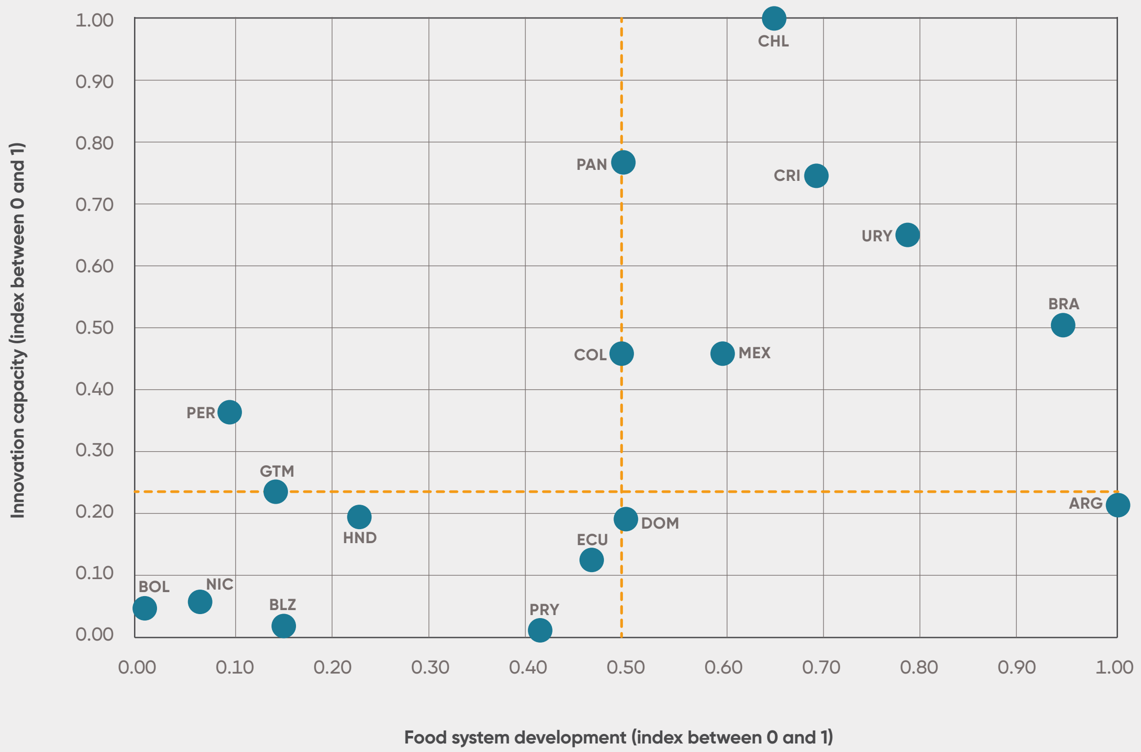
2b. Disaggregated ICI scores of LAC countries



Sources: Elaborated by authors based on Schwab (2019), ASTI (2023), SCImago (2023), and World Bank (2023).
Notes: For more details on the ICI, see Nin-Pratt and Stads (2023) and Annex A.

Innovation and food systems are to a large extent interconnected because the factors that influence a country's ability to innovate are precisely the factors that determine the development of its food system. **Figure 3** demonstrates this positive correlation between FSDI and ICI values in LAC. Most LAC countries fall into one of two quadrants defined by the median values of the indices. The group of countries with low food system development and low innovation capacity includes Belize, Bolivia, Ecuador, Honduras, Nicaragua, and Paraguay. Additionally, scores for Guatemala and Peru are low for food system development and average for innovation capacity, while the Dominican Republic scores low in innovation capacity and average in food system development. Countries with high food system development and high innovation capacity include Brazil, Chile, Costa Rica, Mexico, and Uruguay. Additionally, Panama's and Colombia's scores are high for innovation capacity and average for food system development, while Argentina's are moderate for innovation capacity and high for food system development.

Figure 3. Food system development versus innovation capacity



Sources: Elaborated by authors based on Schwab (2019), ASTI (2023), FAO (2022), SCImago (2023), USDA-ERS (2023), and World Bank (2023).
Note: For more detail on the FSDI and ICI, see Annex A.

/3/

AGRICULTURAL RESEARCH SYSTEMS IN LATIN AMERICA AND THE CARIBBEAN: RECENT TRENDS AND CHALLENGES

As shown in Figure 2b, there are significant differences in human capital and research capacity among LAC countries. Chile, Costa Rica, Brazil, Uruguay, Colombia, Mexico, Panama, and Argentina score high in these two areas, and these factors contribute to the overall higher development of their national science and research systems. Considering differences in human capital, research, and innovation capacity is crucial when assessing the overall performance of agricultural research systems in the region.

This section offers a brief update on the findings of Stads et al. (2016) on agricultural R&D capacity and investment. It focuses on ten LAC countries for which the ASTI program recently collected timeseries data for the period 2017–2020: Belize, Bolivia, Costa Rica, the Dominican Republic, Ecuador, Guatemala, Honduras, Nicaragua, Panama, and Peru.[1] Drawing from these updated ASTI datasets, a clear picture of the capacity and investment trends of these countries with relatively smaller R&D systems, as well as the challenges they are facing, is provided. These findings will then be compared with those of countries with larger and/or more advanced agricultural R&D systems in Section 4 of this report.

In this analysis agricultural research is herein defined to include research on crops, livestock, forestry, fisheries, and natural resources, as well as on-farm postharvest research. Although detailed data were collected from a large number of private-sector companies, coverage was insufficient to allow an accurate overview of the region's private involvement in agricultural research to be reported. The data and analyses presented in this report therefore only include agricultural research performed by the government, higher education, and nonprofit sectors. For more information on the role of the private sector in agricultural R&D in LAC, please consult **Box 1**.

This report focuses on national agricultural research capacity, investment, and outputs only. Data on the contributions of international or regional agricultural research agencies operating in LAC, such as the centers of the CGIAR, the Inter-American Institute for Agricultural Cooperation (IICA), or the Agronomic Center for Research and Education (CATIE) have therefore been excluded. Similarly, Zamorano is a Panamerican school with regional status. Given that it is technically not a Honduran R&D agency, data for Zamorano are excluded in country totals for Honduras throughout this report.[2]

1. ASTI collected primary data through national survey rounds in close collaboration with country focal points based at national agricultural research institutes in the ten LAC countries. These focal points distributed detailed survey forms to the principal agencies known to conduct agricultural research in a given country, including those in the government, nonprofit, and higher education sectors. Although private companies were targeted as well, the overall response rate of the private sector was too low to yield useful results.

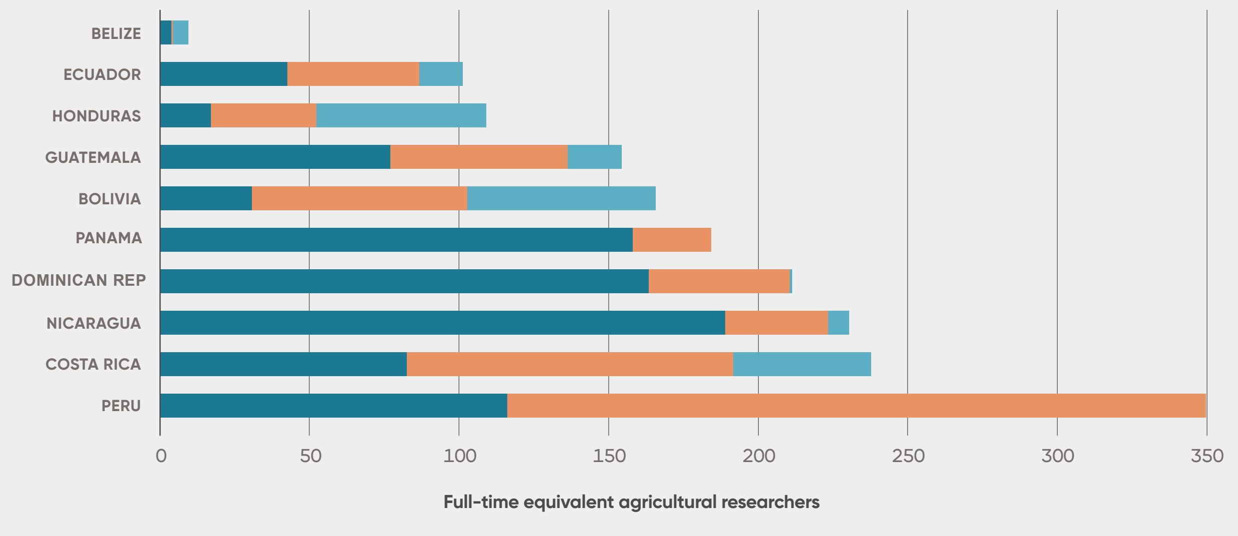
2. Zamorano is larger than any individual Honduran agricultural R&D agency in terms of research staff. In 2020, Zamorano employed 62 FTE agricultural researchers, considerably more than Honduras' Directorate of Science and Agricultural Technology (DICTA; 17 FTEs in 2020) and the Honduran Foundation for Agricultural Research (FHIA; 43 FTEs in 2020) (Stads and De los Santos, 2023).

3.1. Institutional composition of agricultural R&D

The landscape of agricultural R&D[3] in LAC is highly complex, comprising a large number of governments, higher education, nonprofit, private, and international research agencies.[4] It is worth noting that agricultural research systems vary significantly in size across countries, which is not unexpected, given the substantial differences in the size of their economies and populations. Among the ten countries covered in this section, Peru has the largest agricultural research system, employing 350 full-time equivalent (FTE) researchers in 2020.

Across the region, the government sector is the leading employer of agricultural researchers, with 50 percent of agricultural researchers in the ten countries combined working for government R&D agencies in 2020. The higher education sector employed 38 percent of agricultural researchers, while nonprofit agencies employed 12 percent **(Figure 4)**. However, there is significant variation across countries. Peru, for example, stands out from most countries in LAC (and beyond) in that its higher education sector plays a much more significant role in agricultural R&D than the government sector. In contrast, Panama, the Dominican Republic, and Nicaragua have limited involvement of the higher education sector in agricultural R&D. Bolivia and Honduras differ from many of their Latin American counterparts in that their nonprofit sectors play significant roles in the agricultural research system.

Figure 4. Institutional composition of public agricultural research, 2020



Source: Compiled by authors from ASTI (2023).

3. Agricultural R&D is defined to include research on crops, livestock, forestry, fisheries, and natural resources, as well as on-farm postharvest research.

4. The private (for profit) sector is excluded from the analysis in this report because data for many private firms were not accessible. Data on the contributions of international agricultural R&D operating in the region, such as CGIAR, are also excluded.

Box 1. Private-sector agricultural R&D in Latin America and the Caribbean

In LAC, private agricultural research and development has gained significant traction over the past few decades, particularly in the region's more developed nations. The diversification of agricultural production, more sophisticated value chains along with more complex technological and knowledge markets, have pushed private companies to invest more in R&D. The private sector has contributed considerably to advancements in crop varieties, farming technologies, inputs, and postharvest handling and processing systems, thereby strengthening LAC's position in global markets. Unfortunately, comprehensive investment data for the region's private firms were not available, making it is difficult to quantify public versus private investments, or provide insight into developments over time.

Overall, **the private sector plays a more prominent role in agricultural R&D in LAC's larger and/or more advanced countries —including Argentina, Brazil, Chile, Colombia, Costa Rica, Mexico, and Uruguay— than it does in many of the smaller nations.** In Brazil, for example, private companies have substantially contributed to the development of new and improved soybean, maize, sugarcane, fruit, and vegetables varieties, while in Argentina, local companies have emerged as major actors in seed R&D for soybean and maize. In addition, the private sector has been the key driver behind the release of new horticultural varieties in Chile, Colombia, and Mexico, especially for grapes, avocados, and vegetables.

Costa Rica has become an important hub for private R&D due to the clustering of multinational companies like Chiquita Brands International and Dole, which have set up sizable research centers in the country. Chiquita's research focuses on banana genetic improvement, post-harvest, and crop protection, while Dole conducts research on fruit-related physiology, genetic improvement, biocontrol, and micropropagation. Both companies are also members of CORBANA, a non-profit organization that advocates for the interests of Costa Rican banana producers. Similarly, Starbucks established its 240-hectare global coffee R&D facility in Costa Rica in 2013.

In many smaller and/or less advanced countries in LAC, private investment in R&D is typically more limited, and public agencies or spill-ins from abroad remain their primary sources for new varieties or technologies. For instance, Guatemalan banana growers rely heavily on the research conducted by Chiquita and Dole in Costa Rica. Large global corporations such as Cargill, Monsanto, and Syngenta have established significant R&D facilities throughout LAC and collaborate closely with local universities and research institutions. Skretting, a global player in aquafeed, has set up a research center in Ecuador to develop nutritional innovations for shrimp, and an increasing number of biotechnological companies are conducting R&D in Costa Rica, Guatemala, Honduras, and the Dominican Republic. Despite some multinationals operating sizable research operations in some smaller countries, investment by local companies tends to be more restricted. Instead of conducting in-house research, many of these agribusinesses often outsource their R&D needs to local government research agencies or universities.

In an effort to spur private investment in agricultural research, governments throughout LAC have implemented various incentives. These include **income-tax exemptions and tax allowances for capital expenditures on R&D**, as well as **requirements for private participation in projects funded through competitive funds to promote commercial viability.** Some countries have gone a step further by establishing national innovation centers that facilitate collaboration and knowledge-sharing between public and private entities. One example is the Ciudad del Saber in Panama City, which hosts over 200 organizations, including universities, research centers, and private companies. The goal is to create an environment that fosters innovation and encourages the development of new technologies and solutions in the agricultural sector and beyond.

3.2. Human capacity in agricultural R&D

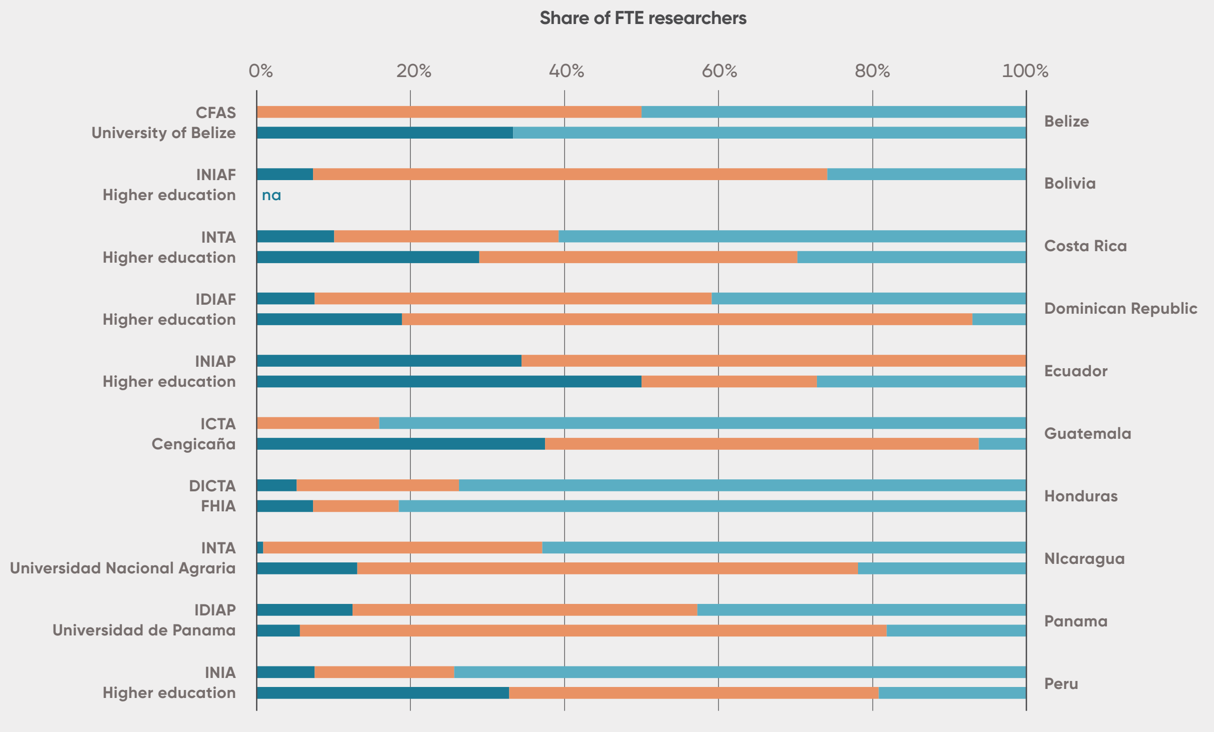
While **Figure 4** shows total agricultural R&D capacity numbers in terms of FTE researchers, **Figure 5** focuses on the quality of this capacity by taking a closer look at the degree levels of these researchers. The data reveals that a majority of agricultural researchers in the ten countries hold BSc or MSc degrees, with only a few researchers holding PhD degrees. On average, government research institutes employ researchers with lower qualification levels than universities. In some countries, the difference in the official status of government and university-based scientists hinders government agencies from offering competitive salaries and benefits, leading to the departure of qualified researchers to universities and the private sector.

Additionally, some experienced senior researchers have been reassigned to non-research positions, resulting in critical staffing gaps at research institutes. Furthermore, promotional opportunities at government agencies are often based on seniority rather than merit, making them unattractive employers for young and ambitious scientists. These factors have contributed to a lack of critical mass of PhD-qualified researchers in many national agricultural research institutes. Belize and Guatemala employ none, Honduras only one, and Bolivia and Nicaragua just two **(Table 1)**. These extremely low numbers of PhDs are worrying, as a minimum number of PhD-qualified scientists is necessary for effective conception, management, and execution of high-quality research, communicating with policymakers, donors, and other stakeholders, and securing competitive funding. To address these issues, appropriate conditions and incentives need to be established to encourage the long-term commitment of researchers at government agencies across the region. This will help attract and retain young and qualified scientists and ensure the development of a strong agricultural research workforce.

Box 2. Quantifying agricultural researcher numbers

ASTI bases its calculations of human resource and financial data on full-time equivalents (FTEs), which take into account the proportion of time researchers spend on research, as opposed to other activities. University staff members, for example, spend the bulk of their time on nonresearch-related activities, such as teaching, administration, and student supervision, which need to be excluded from research-related resource calculations. As a result, four faculty members estimated to spend 25 percent of their time on research would individually represent 0.25 FTEs and collectively be counted as 1 FTE.

Figure 5. Distribution of agricultural researchers by qualification level, 2020



Source: Compiled by authors from ASTI (2023).
Note: na denotes that data are not available.

Table 1. Number of PhD-qualified researchers employed at national agricultural research institutes in selected LAC countries, headcounts, 2012/13 and 2020

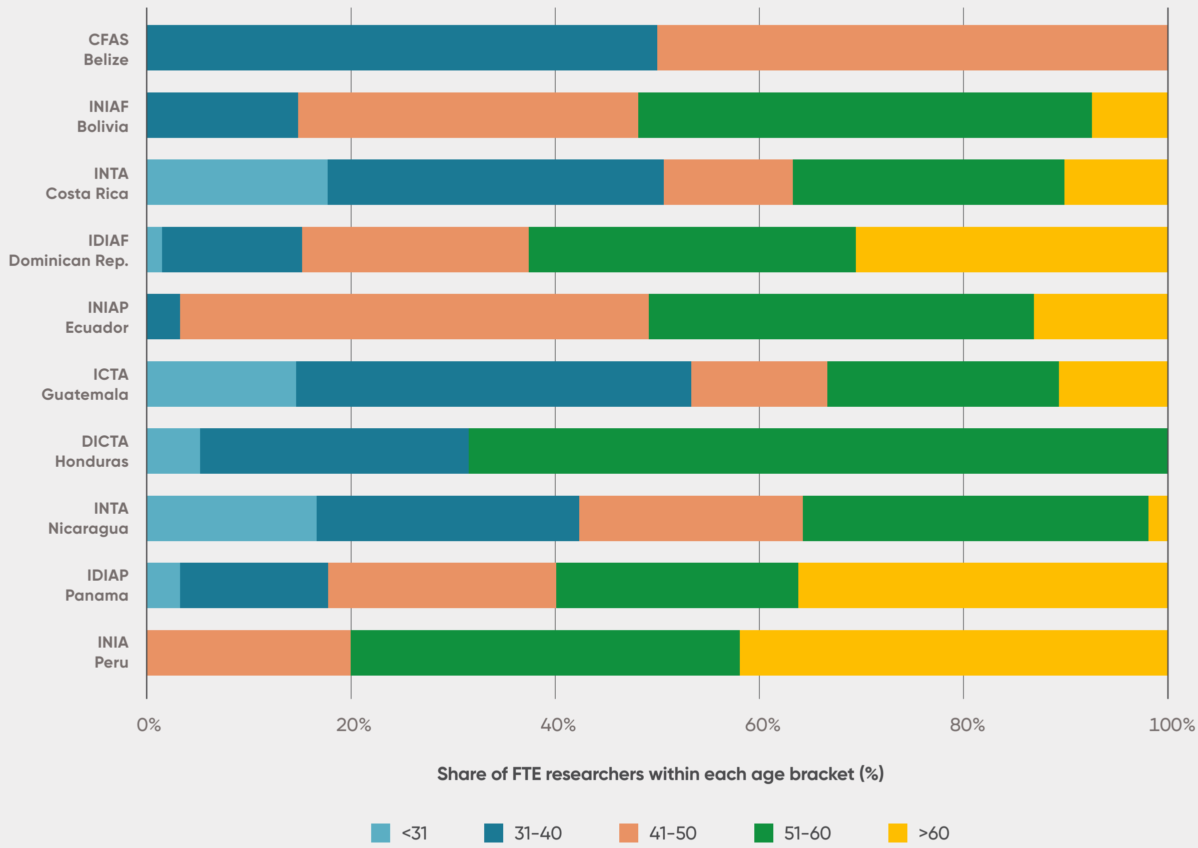
	2012/13	2020
Belize, CFAS	0	0
Bolivia, INIAF	5	2
Costa Rica, INTA	4	8
Dominican Republic, IDIAF	13	10
Ecuador, INIAP	17	21
Guatemala, ICTA	3	0
Honduras, DICTA	1	1
Nicaragua, INTA	6	2
Panama, IDIAP	11	19
Peru, INIA	8	8

Source: Constructed by authors based on ASTI (2023).
Note: Data for Central American countries and the Dominican Republic are for 2012, data for Bolivia, Ecuador, and Peru are for 2013.

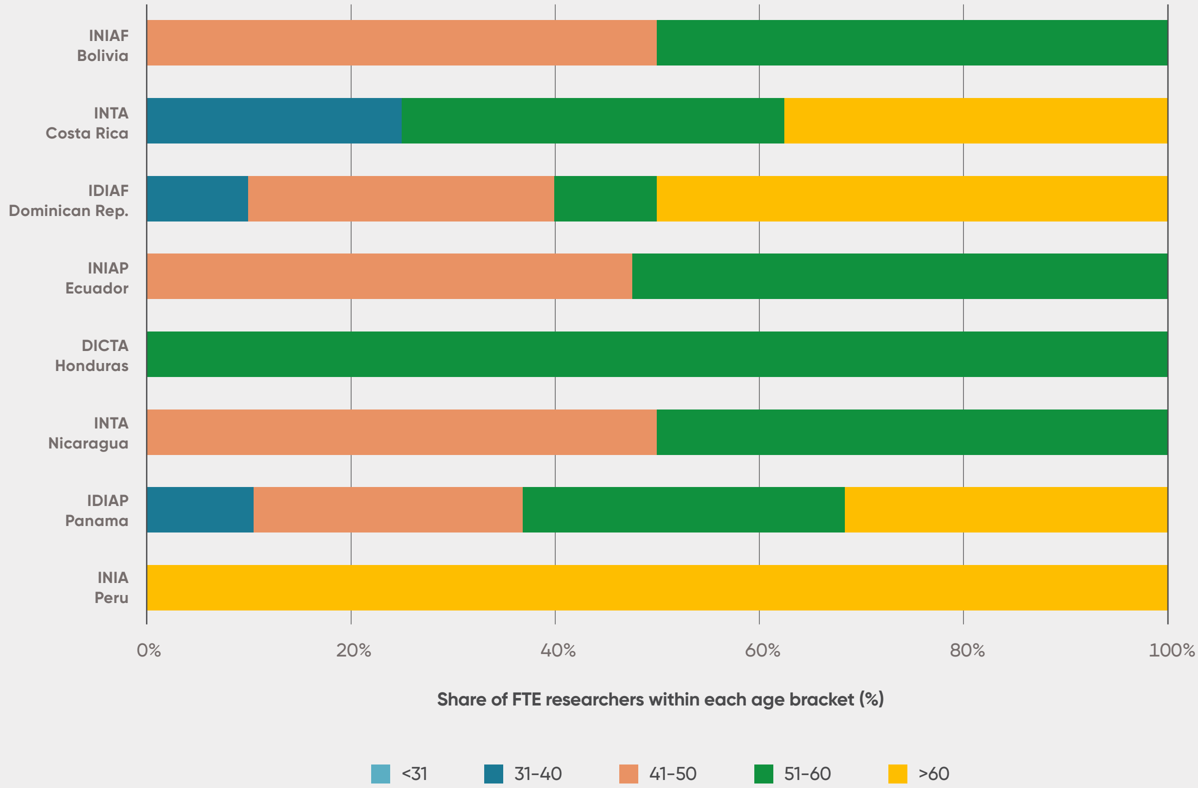
Upon closer examination of the age distribution of agricultural researchers in the ten countries, it becomes evident that many national agricultural research institutes are challenged with an aging pool of scientists. In six out of the ten countries, over half of the researchers are above the age of 51 **(Figure 6a)**. Given that the official retirement age in most of these countries is 60 or 65 years, a significant number of senior researchers are expected to retire in the near future. This situation is particularly severe in Peru, Honduras, and the Dominican Republic. A more in-depth analysis of the age distribution of researchers holding PhD degrees (as opposed to all researchers) paints an even more severe picture. Two-thirds of researchers with PhD degrees in the sample countries are in their fifties and sixties **(Figure 6b)**, underscoring the urgent need for succession planning. Without adequate planning and training, many agencies across LAC will be left without the necessary expertise to lead research programs and mentor junior staff. This will create significant gaps in knowledge, raising concerns about the quality of future research outputs.

Figure 6. Age composition of PhD-qualified agricultural researchers at selected national agricultural research institutes, 2020

6a. All researchers (with PhD, MSc, and BSc degrees)



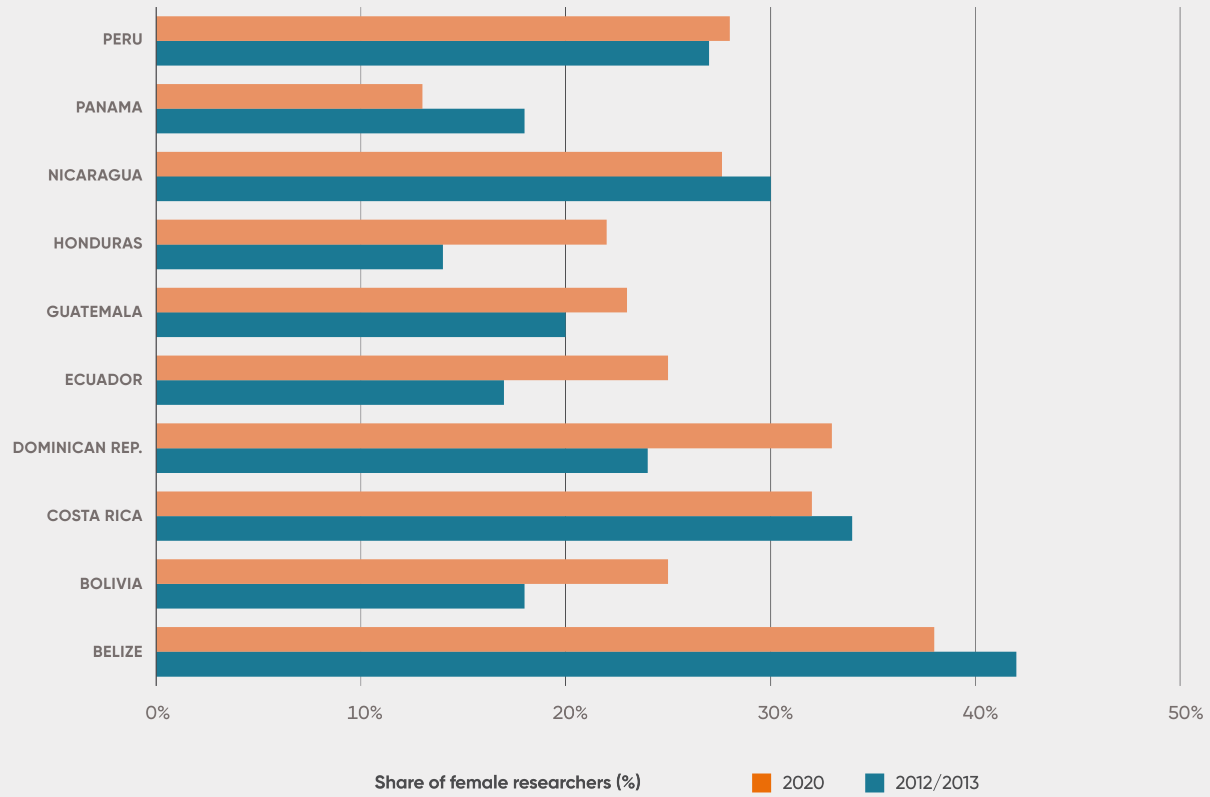
6b. PhD-qualified researchers only



Source: Constructed by authors based on ASTI (2023).
Note: CFAS (Belize) and ICTA (Guatemala) have been excluded from Figure 6b as they did not employ any PhD-qualified researchers in 2020.

Apart from maintaining a well-balanced age distribution of researchers, it is equally significant to ensure a healthy distribution of researchers based on their gender. **Female researchers, professors, and senior managers offer different insights and perspectives than their male counterparts, which is crucial in addressing the unique and pressing challenges faced by female farmers in the region**. Despite progress in increasing female representation in agricultural R&D in seven out of the ten countries between 2012/2013 and 2020, significant gender disparities in research capacity still persist across all countries, indicating that much work still needs to be done to achieve gender equality. As of 2020, the overall share of female agricultural researchers in the ten countries is around 26 percent **(Figure 7)**, which still falls short of the ideal. The highest shares were recorded in Belize, Dominican Republic, and Costa Rica. However, efforts should be made to increase female representation in agricultural research in all countries to ensure a more diverse and inclusive research workforce. This will help in generating more effective and relevant solutions to the challenges faced by farmers, especially women, in the region.

Figure 7. Female participation in agricultural research, 2012/13 and 2020

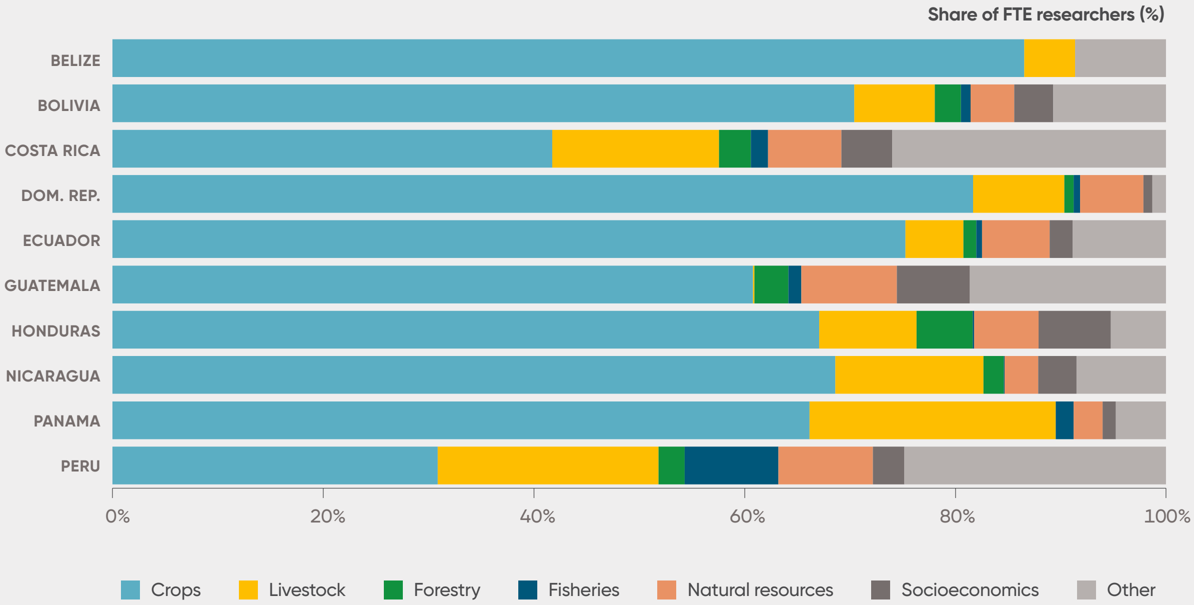


Source: Compiled by authors from ASTI (2023).
Note: Data for Central American countries and the Dominican Republic are for 2012, data for Bolivia, Ecuador, and Peru are for 2013.

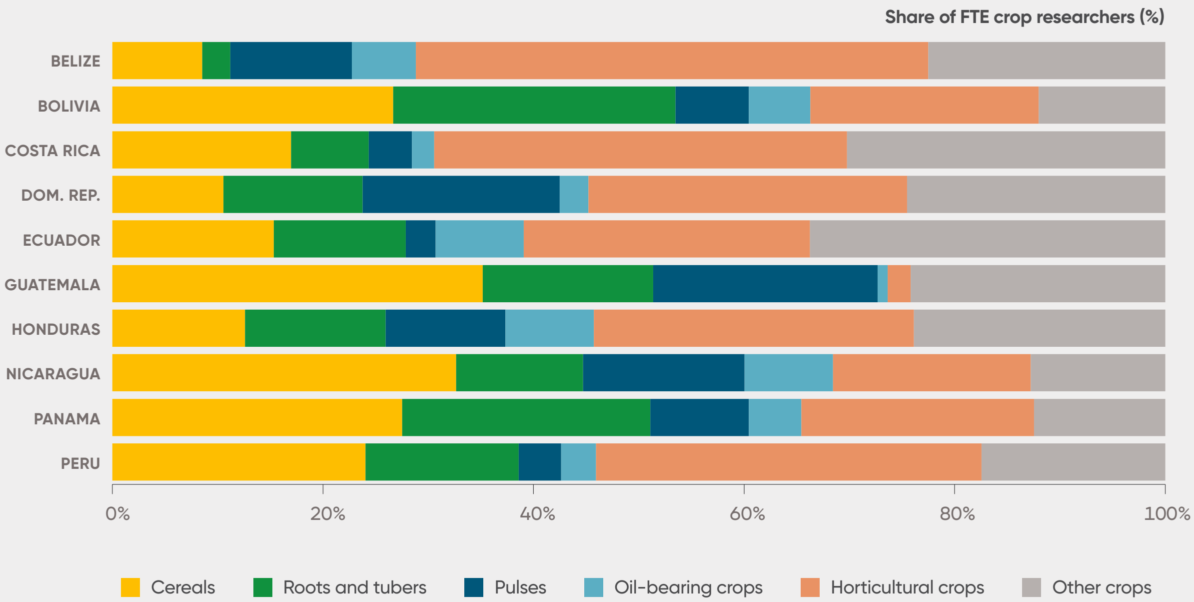
Governments and agricultural research agencies in LAC face significant constraints in allocating scarce resources. Nonetheless, it is crucial that they prioritize funding and staffing for the appropriate types of research and commodities to ensure agricultural R&D has a lasting impact on productivity growth and poverty reduction. To this end, ASTI has gathered detailed information on the allocation of FTE researchers across commodity areas. Crop research was the main focus of 59 percent of researchers in the ten-country sample in 2020, with livestock research accounting for 13 percent **(Figure 8a)**. The remainder of researchers dedicated their attention to forestry, fisheries, natural resources, socioeconomic, and other areas. Notably, Peru and Costa Rica diverged from the other countries in the region by adopting a more balanced distribution of research activities across commodity categories, in contrast to the crop-centric focus of other countries. The most commonly researched commodities across the ten-country sample were horticultural crops, cereals, and roots and tubers. However, there were considerable cross-country variations in research priorities, as highlighted in **Figure 8b.**

Figure 8. Agricultural research focus, 2020

8a. Commodity focus



8b. Crop focus



Source: Compiled by authors based on ASTI (2023).

3.3. Agricultural R&D spending

ASTI also gathered detailed information on the financial resources allocated to agricultural R&D in various countries. Peru was the only country among the sample to exceed 100 million dollars (in 2017 PPP prices) in agricultural R&D spending in 2020, while Bolivia, Costa Rica, and Panama spent 65 million, 38 million, and 34 million, respectively **(Figure 9)**. The remaining countries all spent less than 20 million in 2020. During the 2007–2020 period, collective agricultural R&D spending in the ten countries rose by 45 percent in inflation-adjusted terms, indicating a positive trend, mostly driven by Bolivia and Peru. Bolivia tripled its agricultural R&D spending, but this increase was mainly due to a large influx of donor and development funding, the volatile nature of which resulted in significant fluctuations in spending levels from year to year. Similarly, neighboring Peru experienced considerable growth in agricultural R&D spending, driven entirely by an influx of funding through development bank loans. This funding helped to strengthen the country's agricultural R&D through institutional reforms, staff training, and competitive research and innovation grants In contrast, most other countries in the region reported relatively stable or slightly decreasing agricultural R&D spending levels. However, both Bolivia and Peru face the risk of reverting to past growth performances as has historically occurred when countries receive a significant time-bound loan and cannot sustain investment growth based on government funding. It would be critical to monitor the future evolution of R&D investment and the performance of research systems in these countries.

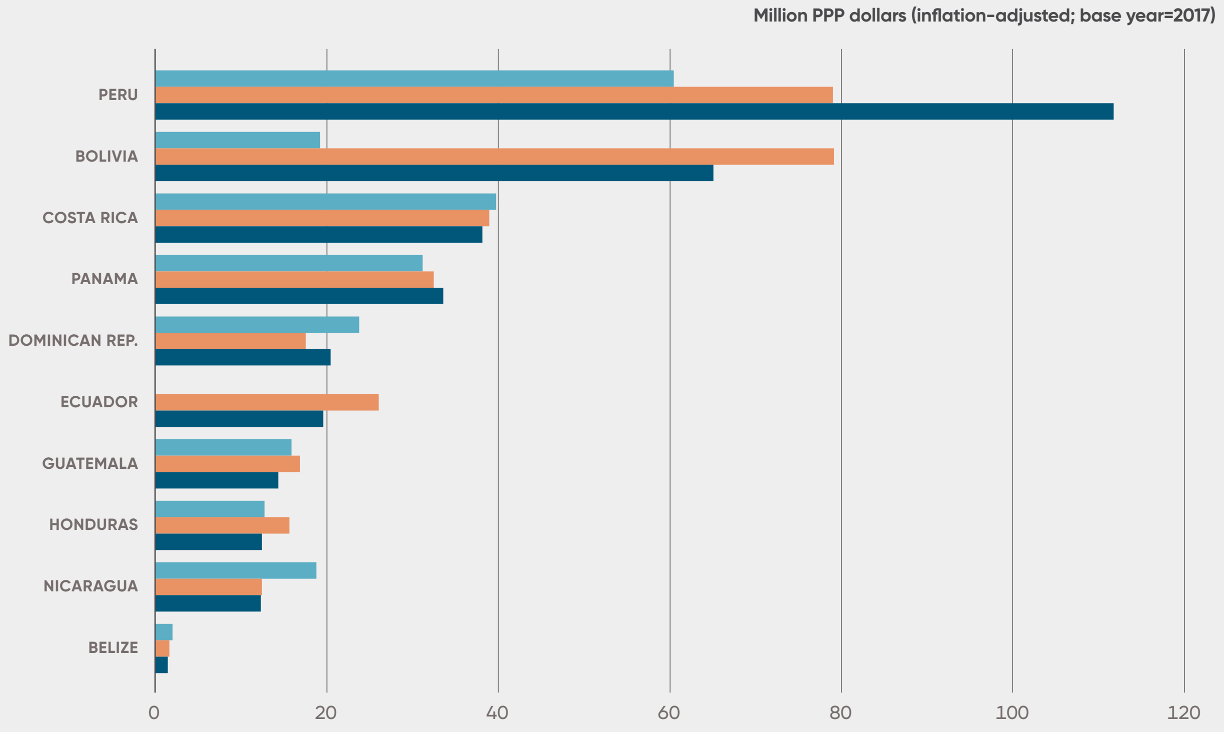
Box 3. Quantifying agricultural research spending

Comparing data on research expenditures is a highly complex process due to important differences in price levels across countries. The largest components of a country's agricultural research expenditures are staff salaries and local operating costs, rather than internationally traded capital investments. For example, the wages of a field laborer or a laboratory assistant at a research facility are much lower in Honduras than they are in any European country; similarly, locally made office furniture in Bolivia will cost a fraction of a similar set of furniture bought in the United States.

Standard market exchange rates are the logical choice for conversions when measuring financial flows across countries; however, they are far from perfect currency converters for comparing economic data. At present, the preferred conversion method for calculating the relative size of economies, or other economic data such as agricultural research spending, is the purchasing power parity (PPP) index. PPPs measure the relative purchasing power of different currencies by eliminating national differences in pricing levels for a wide range of goods and services. They are also used to convert current GDP prices in individual countries to a common currency.

In addition, **PPPs are relatively stable over time, whereas market exchange rates fluctuate considerably** (for example, fluctuations in the U.S. dollar and euro exchange rates in recent years).

Figure 9. Agricultural research spending, 2007, 2014, and 2020

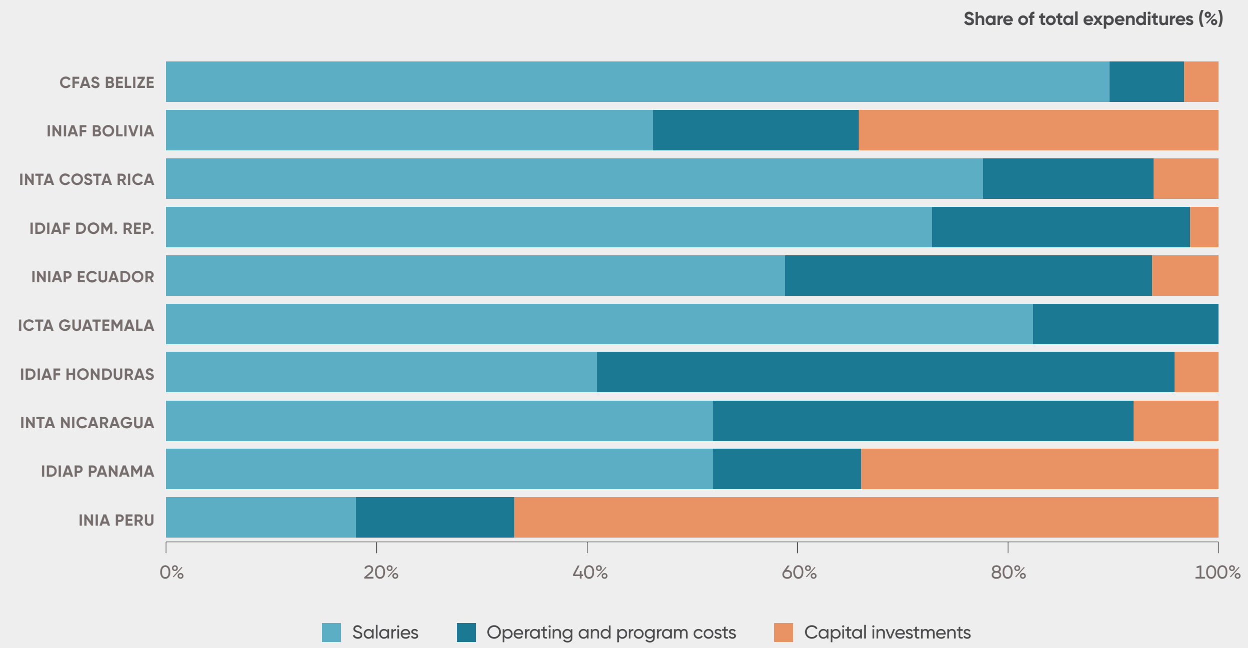


Source: Compiled by authors based on ASTI (2023).

A closer look at the composition of agricultural R&D spending among national agricultural research institutes reveals that the bulk of spending was allocated to salary costs. During 2017–2020, salary costs accounted for more than two-thirds of total spending at the national institutes of Belize, Guatemala, Costa Rica, and the Dominican Republic **(Figure 10)**. Once again, Peru and Bolivia stand out, in that they spend a higher portion of their total R&D cost on capital investments. This is not surprising, given that the large influx of funding through development bank loans in these countries allowed for significant rehabilitation of R&D infrastructure. Panama also invested heavily in capital expenditure due to the construction and furnishing of its national agricultural research institute's new headquarters.

Merely analyzing absolute research expenditures can only provide so much insight. Another way of comparing the level of commitment to agricultural R&D investments across countries is by measuring total agricultural R&D spending as a percentage of agricultural gross domestic product (AgGDP). This relative measure extends beyond absolute agricultural R&D spending levels and indicates the intensity of investments. Although some international organizations have established (somewhat arbitrary one-size-fits-all) agricultural R&D investment targets of at least 1 percent of AgGDP, only one of the ten sample countries invested more than 1 percent in 2020. Panama invested 1.12 percent of its AgGDP in agricultural R&D, a significant improvement from previous years **(Figure 11)**.

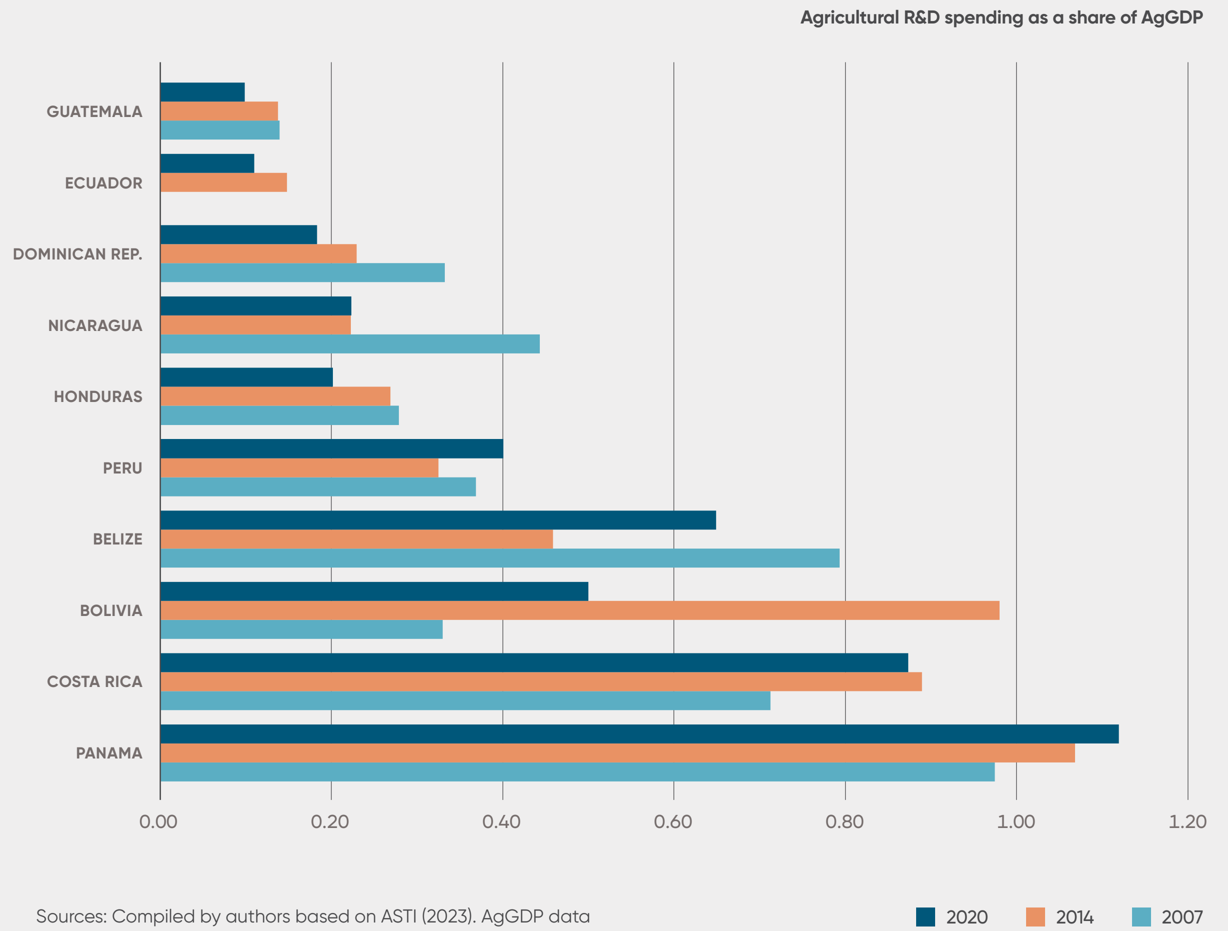
Figure 10. Distribution of agricultural R&D expenditures by cost category, 2017–2020 averages



Source: Compiled by authors based on ASTI (2023).

With an intensity ratio of 0.87 percent, Costa Rica also came relatively close to the 1 percent target. However, research investment levels relative to agricultural output in all other countries were considerably lower, with five of the ten sample countries investing less than 0.25 percent. Such low R&D investment levels are often deemed inadequate in effectively addressing farm productivity and other challenges faced by rural communities. Another concerning trend is that these countries with low investment levels have experienced a steady decline in their agricultural research intensity ratios over time, indicating that agricultural research spending has not been keeping up with the growth in agricultural output.

Figure 11. Agricultural research intensity ratios by country, 2007, 2014, and 2020



Sources: Compiled by authors based on ASTI (2023). AgGDP data were taken from World Bank (2023).

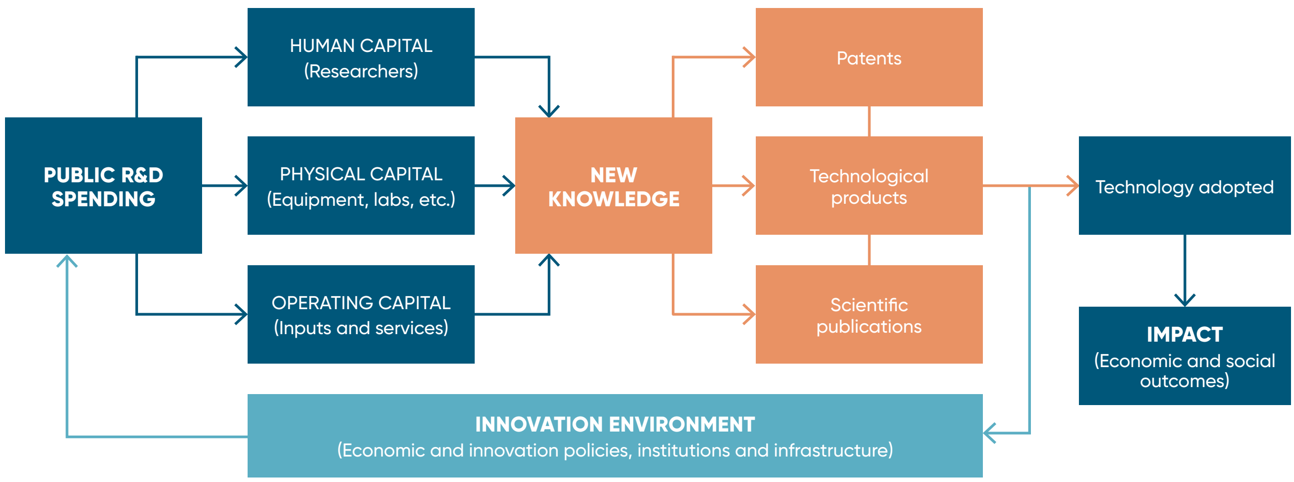
/4/

AGRICULTURAL RESEARCH CAPACITY

This section aims to analyze the scientific capacity and the development of public agricultural research systems in LAC, with a specific focus on the production process that generates new knowledge, as illustrated in the central part of Figure 12. The relationships between agricultural research outputs and their impact, as depicted in the right portion of Figure 12, will be explored in Section 5.

Figure 12 illustrates the research system as a production unit that generates new knowledge. The inputs required for this system to produce outputs include R&D spending, which encompasses physical resources (machinery, labs, equipment) and human capital (researchers), as well as operating capital used to procure inputs like chemical products and cover services like electricity. The outputs obtained from this production process can be classified into direct research outputs (scientific publications and patents), and technological products. Publications are a by-product of technological outputs and contribute to the advancement of scientific knowledge by formalizing and making public advancements in different research fields. Technological products can take the form of tangible goods, wherein the newly generated knowledge is incorporated into a physical product like improved seeds or new machinery. Alternatively, technological products can be intangible or "pure knowledge", such as novel resource management practices that enhance production output without increasing production cost. It is important to note that research alone does not impact the economy unless technological products are adopted by producers and transform into "innovations", thereby translating knowledge into economic value. However, not all technological products automatically become innovations. The external innovation environment plays a major role in facilitating or impeding the innovation process (Guan and Chen, 2012, Geisler, 1995, Pakes and Griliches, 1980). Additionally, a lack of innovation can also be attributed to issues in the research system, such as a lack of demand for the technologies produced.

Figure 12. The agricultural innovation process



Sources: Elaborated by authors based on Geisler (1995), Guan and Cheng (2012), Pakes and Griliches (1980), and Conte et al. (2009).

Table 2 presents various aspects of research system performance, highlighting their links to environmental factors. The first set of indicators focuses on the relationship between outputs and the inputs used in producing new knowledge. These indicators include costs per unit of output, researcher productivity, and total spending per researcher. The human capital indicator considers the number and qualifications of researchers within the system, while the cost structure and the relationship between human and physical capital affect the production process. Factors such as salaries, operating expenditures, and program costs are crucial determinants of research system performance. The overall performance of the research system is also influenced by its scale, which affects costs, productivity, and output quality. While the maximum scale of the research system is constrained by structural factors such as the size of the economy, the agricultural sector, demand for innovation, and the level of economic development, countries still possess options to define the size of their R&D system within those limitations. Given that data on technological outputs are not available for country comparisons at this level, we use scientific publications as a proxy for research outputs. Since publications are a by-product of technological outputs, they serve as an indicator reflecting the productivity and quality of research conducted within a country.

To assess the overall performance of national agricultural R&D systems in LAC, this section relies on two main data sources. The first is IFPRI's ASTI database, which offers comprehensive information on the institutional structure, capacity, expenditures, and funding structure of agricultural research systems. ASTI has recently updated its datasets to the year 2020 for ten countries in LAC (Belize, Bolivia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Nicaragua, Panama, and Peru) with IDB support (as discussed in Section 3). The available ASTI data for the remaining LAC countries only covers the period up to 2013. To estimate the agricultural R&D investment levels of these countries in more recent years, extrapolations were made based on the annual growth rates of their agricultural GDP. Complementing the ASTI data, detailed information on the total number and quality of scientific publications in agricultural and biological sciences at the country level is obtained from SCImago (2023). This data serves to represent the direct research output.

Table 2. Factors contributing to the performance of the production of scientific knowledge in agriculture

CONTRIBUTING FACTOR	DESCRIPTION
Scale	Size of the research system, critical mass
Input–Output relationship	Cost per published article, the productivity of researchers, spending per researcher
Human capital	Number and qualification of researchers
Input mix, cost structure	Relationships between human, physical, and operational capital
Institutional composition of public R&D	Allocation of national R&D expenditure among government research agencies, higher education agencies, and non-profit agencies
Environmental factors	Development of overall national R&D system, quality of education, access to higher education, innovation policy

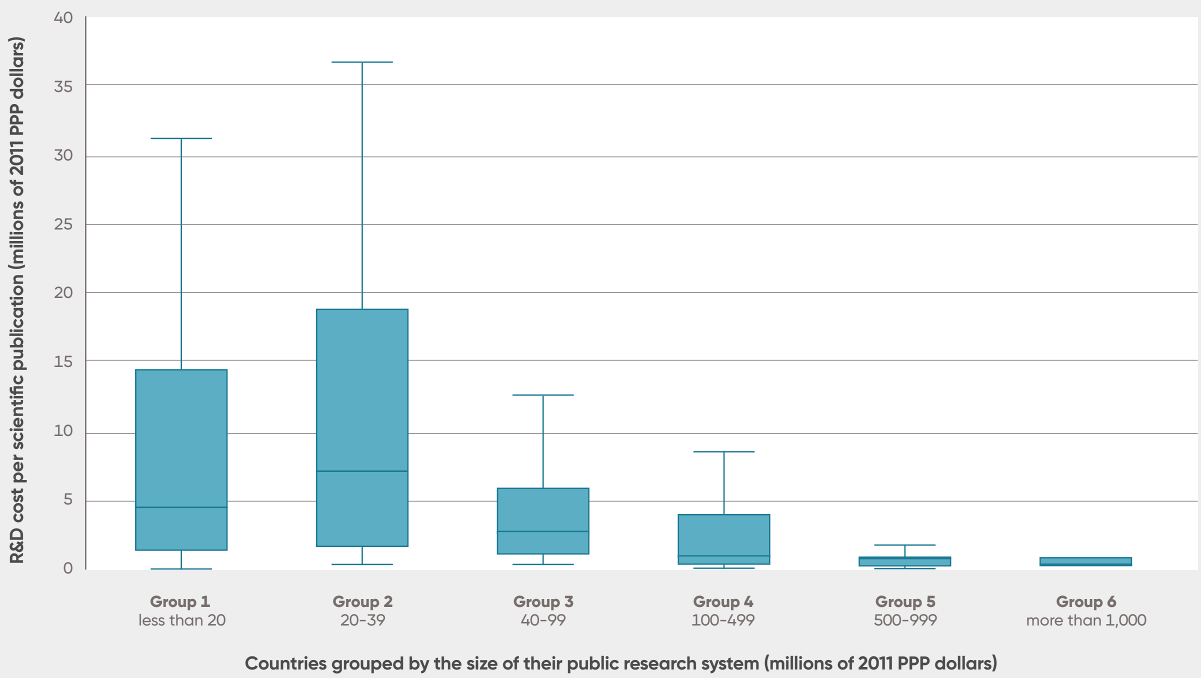
Source: Constructed by authors.

Based on these two data sources, the following variables and indicators were selected and compiled to provide a comprehensive assessment of the research system's capacity: R&D expenditure per scientific publication; cost and output per researcher; the share of salaries and capital in total research costs; the institutional composition of R&D (contribution of government and higher education agencies in the system); and R&D investment as a measure of the size of the research system. For detailed information regarding the data sources and the calculation methodologies for these indicators, please refer to **Annex B**.

4.1. Country grouping and reference countries for the comparative analysis

Countries were categorized based on the size of their agricultural research system, which is a crucial factor to consider when conducting cross-country comparisons. **Figure 13** provides an illustration of the correlation between research and development (R&D) spending and scientific output in agronomic and biological sciences in 124 countries around the world, segmented according to the size of their public agricultural research system. The figure

Figure 13. Agricultural R&D system size and scientific output for 124 countries grouped by the size of their research system, 2010–2013 averages



Sources: Constructed by authors based on ASTI (2023) and SCImago (2023).
Notes: (a) United States, China, India, and Brazil are not included as they appear as outliers in a general comparison because of the large size of their research systems. (b) The box plots provide a visual representation of the five-number summary for each group of countries. The box within the plot represents the interquartile range, which encompasses the middle 50 percent of scores. The median, denoting the midpoint of the data, is indicated by the line that divides the box into two parts. The lower and higher whiskers represent respectively the bottom and top 25 percent of values within each group. On the other hand, the higher whisker represents the top 25 percent of values within each group. The lowest score, excluding outliers, is displayed at the end of the lower whisker, while the highest score is represented by the end of the higher whisker.

emphasizes the substantial influence of R&D investment on research performance. The data indicates that countries investing less than 20 million PPP dollars annually allocate an average of over 11 million PPP dollars per published article. This amount increases to 38 million PPP dollars for countries spending between 20 and 40 million PPP dollars per year. However, countries investing between 40 and 100 million PPP dollars in R&D witness a significant decrease in spending per published article, with an average of 6 million PPP dollars. Meanwhile, countries spending between 100 and 500 million PPP dollars in R&D observe a further reduction to 3 million PPP dollars per article. While these findings pertain specifically to published articles, they likely reflect a broader trend encompassing other research outputs. These results can be attributed to various factors, but it is noteworthy that the low number of publications per R&D dollar spent may indicate a comparatively less developed research system in these countries.

The process of measuring and assessing the performance of various agricultural R&D systems across LAC can be broken down into several steps. The first step entails grouping countries by the size of their agricultural research system. In the context of LAC, small research systems were defined as those investing around 30 million dollars per year or less on average (in 2011 PPP prices). This group comprises Belize, Nicaragua, Honduras, Guatemala, the Dominican Republic, Paraguay, Costa Rica, Panama, and Ecuador. The group of countries with medium-sized agricultural research systems consists of Bolivia, Colombia, Peru, Uruguay, and Chile. All the countries in this group spend around 100–300 million dollars per year on agricultural R&D (in 2011 PPP prices). The large research systems group included only Argentina, Brazil, and Mexico, countries that during 2015–2020 invested an average of 670, 2,660, and almost 800 million dollars per year (in 2011 PPP prices), respectively. The following paragraphs will highlight the performance of agricultural research systems in LAC countries with small, medium-sized, and large agricultural research systems.

After establishing the country groups for analysis, the next step is to identify reference countries that serve as benchmarks for assessing the development of agricultural research in other countries. Based on **Figure 3**, four countries emerged as prominent candidates for reference: Brazil (representing large research systems), Chile and Uruguay (representing medium-sized research systems), and Costa Rica (representing small research systems). These countries exhibited the highest innovation capacity and food system development scores. Upon further analysis of the indicators and sub-indices that make up the FSDI and ICI, two additional countries with small research systems, namely Panama and Ecuador, emerged as comparable performers to the original four reference countries. Although Panama's food system development index is lower than that of the reference countries, it still surpasses the regional average, and most importantly, it shows a high score in the innovation capacity index, second only to Chile. Ecuador is noteworthy for its outlier status among small countries, with a lower score in the innovation capacity index, yet significant improvements in human capital and the performance of its research system. With the selection of country groups and reference countries, meaningful comparisons can now be made between countries within each group, enabling valuable insights into their relative performance.

4.2. Comparative Analysis of Agricultural Research Systems Across Country Groups

COUNTRIES WITH SMALL AGRICULTURAL RESEARCH SYSTEMS

Table 3 assesses the performance of research systems in LAC countries with small agricultural research systems. It quantifies each of the performance areas identified in **Table 2**. The data reveal that the small reference countries (Ecuador, Costa Rica, and Panama) have stronger and more developed agricultural research systems compared to the other countries in this group. These reference countries employ a higher number of researchers with advanced degrees, spend more per researcher on R&D, and allocate their research resources more evenly across operating costs and capital investments. Moreover, the productivity of researchers in the reference countries is also considerably higher than in other countries with small research systems. Overall, the data underscore the vital role of human capital in the development of strong research systems.

COUNTRIES WITH MEDIUM-SIZED AGRICULTURAL RESEARCH SYSTEMS

The left-hand columns of **Table 4** compare the performance of medium-sized agricultural research systems in LAC, with Chile and Uruguay serving as reference countries. Overall, Chile, Colombia, and Uruguay have more developed research systems than Bolivia and Peru. Chile outperforms the other countries in this group with a productivity of 2.1 publications per researcher per year, while the average for the other countries is just 0.98. This gap in scientific development can be attributed to differences in human capital, although the differences between countries with medium-sized systems are smaller than in the case of countries with small research systems. The most significant difference between Chile and other countries in this group is the proportion of researchers with PhD degrees, which is 37 percent in Chile and between 22 and 26 percent in the other countries. Another important difference is the share of salaries in total research costs, which is above 50 percent in Chile and Uruguay, but only 19 percent in Peru. Additionally, the ratio of government spending to higher education spending on agricultural R&D is significantly higher in Chile, Colombia, and Uruguay than in Bolivia and Peru.

COUNTRIES WITH LARGE AGRICULTURAL RESEARCH SYSTEMS

The columns on the right-hand side of **Table 4** compare the performance of LAC's large agricultural research systems. Brazil's investment in R&D stands out, spending nearly four times more than Argentina and Mexico relative to the number of researchers it employs. Both Argentina and Mexico allocate considerably fewer resources per researcher than Brazil, resulting in lower output overall. In fact, the average researcher in Brazil publishes 2.1 articles per year, compared to just 0.8 in Mexico and 0.5 in Argentina. This higher productivity in Brazil is linked to the country's greater proportion of researchers holding PhD degrees. Salaries make up the highest share of total costs in all three countries, but Mexico allocates a greater proportion of R&D expenditures to salaries compared to Brazil and Argentina. In Brazil, government agencies play a significant role in agricultural R&D, accounting for over 70 percent of total public agricultural R&D spending. In Argentina, this figure is 50 percent, and in Mexico, it is 39 percent.

Table 3. Comparisons of countries with small agricultural research systems

								Reference countries			
	BLZ	NIC	HND	GTM	DOM	PRY	Average	ECU	PAN	CRI	Average
R&D spending, 2015–2020 (million 2011 PPP$)	2	9	12	17	18	32	18	24	26	30	27
Average number of researchers 2015–2020 (FTEs)	9	156	101	143	212	233	169	100	179	235	172
Average number of publications	16	23	37	45	28	59	39	615	311	349	425
Average R&D expenditure per FTE researcher, 2015–2020	0.19	0.06	0.12	0.12	0.09	0.14	0.10	0.24	0.15	0.13	0.17
Number of publications per FTE researcher	1.64	0.12	0.35	0.30	0.14	0.16	0.21	4.54	1.59	1.41	2.52
R&D expenditure per publication	0.11	0.50	0.44	0.42	0.65	0.91	0.58	0.05	0.12	0.11	0.10
R&D expenditure per quality-adjusted publication	0.78	2.84	3.07	2.61	5.62	6.74	4.18	0.13	0.19	0.26	0.19
Quality-adjusted publications per researcher	0.23	0.02	0.05	0.05	0.02	0.02	0.03	1.79	1.00	0.63	1.14
Salary costs in total research cost (%)	89.66	53.46	40.73	82.81	78.20	84.31	67.90	83.19	52.35	77.62	71.05
Operating costs in total research cost (%)	7.20	38.47	55.26	17.19	19.35	13.44	28.74	8.78	14.57	16.19	13.18
Capital costs in total research cost (%)	3.14	8.07	4.02	0.00	2.45	2.26	3.36	8.04	33.08	6.19	15.77
Ratio Operating/Salary	0.08	0.72	1.36	0.21	0.25	0.16	0.54	0.11	0.28	0.21	0.20
Ratio Capital/Salary	0.04	0.15	0.10	0.00	0.03	0.03	0.06	0.10	0.63	0.08	0.27
Ratio Capital/Operating	0.44	0.21	0.07	0.00	0.13	0.17	0.12	0.92	2.27	0.38	1.19
Researchers with a PhD or MSc degree (%)	44.26	42.33	19.69	26.10	n.a.	30.65	29.69	100.00	55.25	59.79	71.68
Researchers with a PhD degree (%)	11.48	2.50	7.09	4.87	n.a.	5.39	4.96	49.28	11.35	18.17	26.26
Researchers with a MSc degree (%)	32.79	39.83	12.60	21.23	n.a.	25.27	24.73	50.72	43.90	41.62	45.42
Researchers with a BSc degree (%)	55.74	57.67	80.31	73.90	n.a.	69.35	70.31	0.00	44.75	40.21	28.32
Ratio R&D expenditure: Government/Higher Education	8.21	3.44	0.59	1.29	4.06	1.37	2.15	1.28	7.02	0.73	3.01
Government share in total R&D expenditure (%)	34.79	74.58	18.53	49.55	79.98	57.76	56.08	47.22	87.54	33.70	56.15
Higher education share in total R&D expenditure (%)	4.24	21.69	31.40	38.33	19.72	42.24	30.68	36.82	12.46	46.46	31.91
Non-profit share in total R&D expenditure (%)	60.97	3.73	50.07	12.12	0.30	0.00	13.24	15.96	0.00	19.84	11.93

Sources: Constructed by authors based on ASTI (2023) and SCImago (2023).

Table 4. Comparisons of countries with medium-sized and large agricultural research systems

						Reference country			Reference country
	BOL	PER	COL	URY	Average	CHL	ARG	MEX	BRA
R&D spending, 2015–2020 (million 2011 PPP$)	55	143	300	93	148	213	674	798	2.660
Average number of researchers 2015–2020 (FTEs)	212	344	1.220	405	545	787	6.611	4.337	6.161
Average number of publications	100	523	1.609	382	653	1.781	3.017	4.178	14.715
Average R&D expenditure per FTE researcher, 2015–2020	0.26	0.42	0.25	0.23	0.29	0.27	0.10	0.18	0.43
Number of publications per FTE researcher	0.58	1.37	1.11	0.86	0.98	2.11	0.48	0.84	2.13
R&D expenditure per publication	0.76	0.27	0.25	0.30	0.40	0.13	0.28	0.25	0.22
R&D expenditure per quality-adjusted publication	2.08	0.64	0.47	0.79	0.99	0.21	0.34	0.29	0.22
Quality-adjusted publications per researcher	0.21	0.59	0.58	0.33	0.43	1.32	0.39	0.70	2.13
Salary costs in total research cost (%)	46.31	18.85	n.a.	52.08	39.08	52.18	79.79	55.64	76.67
Operating costs in total research cost (%)	19.51	15.29	n.a.	32.05	22.28	34.16	14.88	41.35	15.74
Capital costs in total research cost (%)	34.18	65.86	n.a.	15.87	38.64	13.66	5.33	3.00	7.59
Ratio Operating/Salary	0.42	0.81	n.a.	0.62	0.62	0.65	0.19	0.74	0.21
Ratio Capital/Salary	0.74	3.49	n.a.	0.30	1.51	0.26	0.07	0.05	0.10
Ratio Capital/Operating	1.75	4.31	n.a.	0.50	2.19	0.40	0.36	0.07	0.48
Researchers with a PhD or MSc degree (%)	n.a.	63.72	56.49	57.65	59.29	56.72	1.13	1.37	3.38
Researchers with a PhD degree (%)	n.a.	24.73	22.54	26.05	24.44	36.76	20.84	47.47	72.51
Researchers with a MSc degree (%)	n.a.	38.99	33.94	31.60	34.84	19.96	18.46	34.54	21.46
Researchers with a BSc degree (%)	n.a.	36.28	43.51	42.35	40.71	43.28	60.70	17.99	6.03
Ratio R&D expenditure: Government/Higher Education	0.44	0.55	1.99	1.07	1.01	2.83	1.01	0.63	2.72
Government share in total R&D expenditure (%)	19.26	35.60	40.27	50.85	36.50	66.65	50.24	38.70	71.27
Higher education share in total R&D expenditure (%)	44.04	64.40	20.26	47.67	44.09	23.54	49.76	61.30	26.17
Non-profit share in total R&D expenditure (%)	36.70	0.00	39.47	1.48	19.41	9.81	0.00	0.00	2.56

Sources: Constructed by authors based on ASTI (2023) and SCImago (2023).

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THE RELATIONSHIP BETWEEN AGRICULTURAL SECTOR PERFORMANCE AND R&D INVESTMENT IN LATIN AMERICA AND THE CARIBBEAN

This section explores the connection between R&D investment and agricultural sector performance in LAC by investigating the impact of research on agriculture, specifically focusing on changes in productivity.

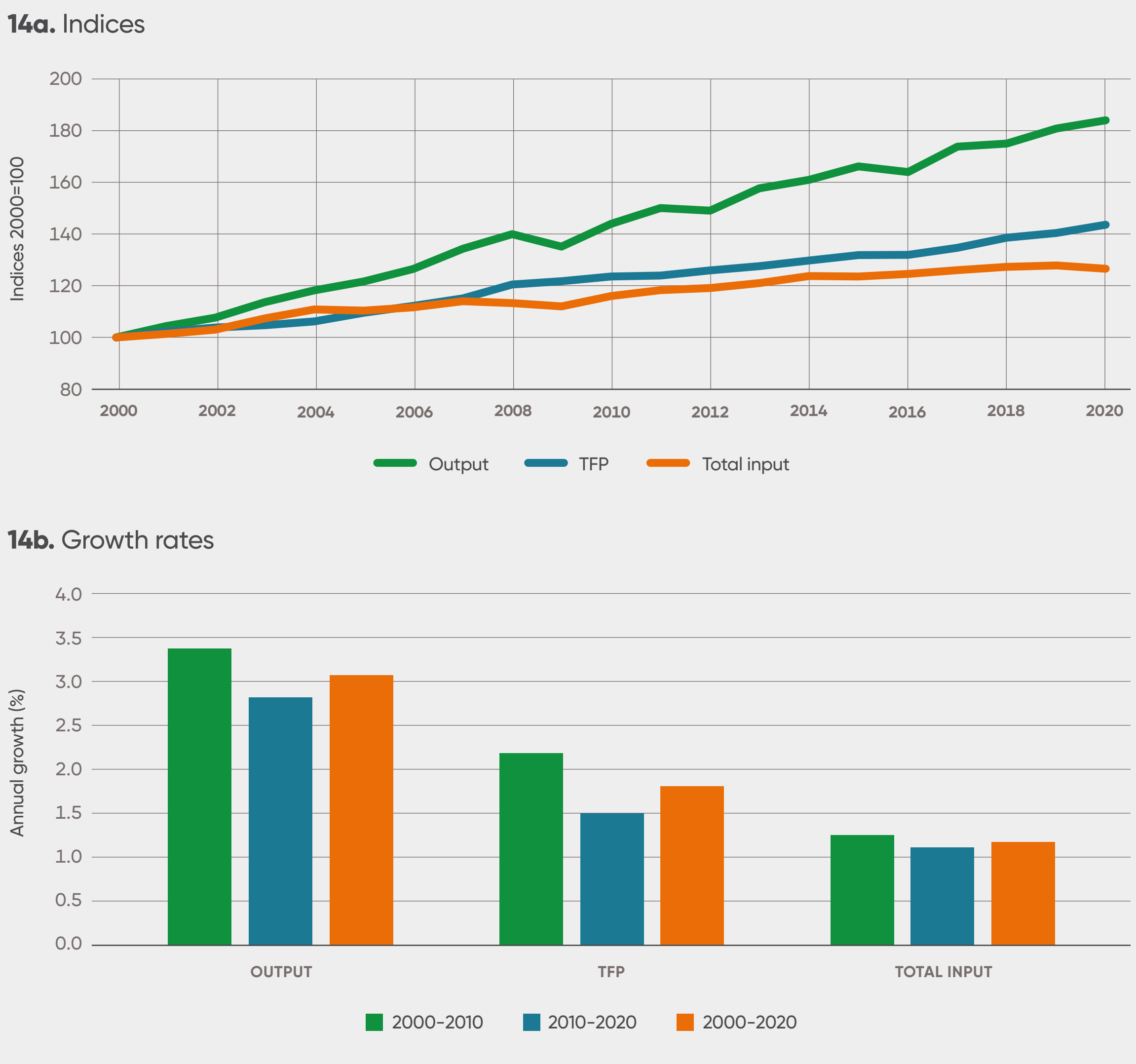
To achieve this, a global model of R&D investment calibrated at the country level is employed that includes public agricultural R&D investment, knowledge spillovers, and environmental factors like temperature and precipitation. The data sources used to construct this model include total agricultural output and inputs from the USDA-ERS database (2023), public agricultural R&D investment data from ASTI (2023), and temperature and precipitation data from Ortiz-Bobea et al. (2021). To address the limited availability of data on private R&D investment, data from Fuglie (2016) was used for allocating private R&D investment to LAC countries. The underlying assumption is that private R&D plays a significant role in countries with larger economies and more advanced food systems, whereas its importance is relatively lower in smaller and less developed economies. Based on these assumptions and private R&D investment estimates, the model calculates the effect of private R&D investment and private spillovers across LAC. The model is calibrated to replicate the observed trends in agricultural output at the country level as a function of input use, public and private R&D investment, knowledge spillovers, temperature, and precipitation. The following analysis presents the results, focusing on trends in output, estimated TFP, and total input, as well as the contribution of R&D investment to TFP growth between 2000 and 2020. The aim is to provide insights for policymakers and stakeholders by examining the relationship between R&D investment and agricultural performance. For details on the calibration of the model and data used, please consult **Annex C**.

Box 4. Total factor productivity

Increasing the efficiency of agricultural production —that is, getting more output from the same amount of resources— is critical for improving food security. Total factor productivity (TFP) is an indicator of how efficiently agricultural land, labor, capital, and other inputs (seed, fertilizer, and so on) are used to produce a country's agricultural outputs (crops, livestock, and so on). TFP is calculated as the ratio of total agricultural outputs to total production inputs, so when more output is produced from a constant amount of resources, TFP increases. R&D activities producing new crop varieties, technologies, and innovations are a crucial driving factor of TFP, but technological spillovers from abroad, higher numbers of skilled workers, investments that favor the development of input and output markets (such as in roads and communications), and government policies and institutions that promote market development and competition are major drivers as well.

During 2000–2020, there was an 84 percent increase in agricultural output in LAC, which corresponds to average annual growth of 3.1 percent **(Figure 14)**. Output growth was not consistent throughout this period, however, with the first decade demonstrating higher average annual growth (3.4 percent) compared to the second decade (2.8 percent). A closer look at the components of output growth reveals that TFP growth has been the main driver of LAC's total agricultural output growth, accounting for 60 percent of the regional increase. During 2000–2020, annual TFP growth was 1.8 percent, on average, while growth in total input averaged just 1.2 percent per year.

Figure 14. Growth in agricultural output, TFP, and inputs, 2000–2020

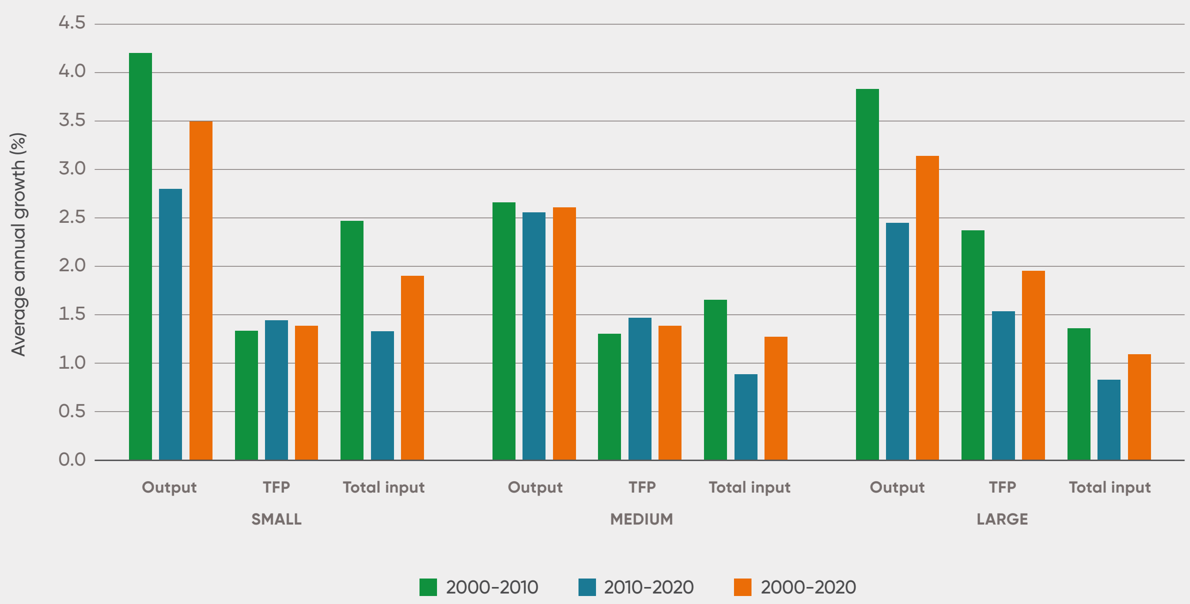


Source: Estimated by authors based on output and input data from USDA-ERS (2023).

The group of countries with small agricultural R&D systems experienced the fastest increase in agricultural output between 2000 and 2020, with growth averaging 3.5 percent per year **(Figure 15)**. This annual growth rate exceeded the one for large systems (3.1 percent) and medium-sized systems (2.6 percent). Interestingly, while the large group's output growth was mostly driven by TFP growth, the small group's growth was primarily the result of increased use of inputs. In other words, the small group's increase in agricultural output resulted mostly from investing in more resources, whereas the large group's growth stemmed predominantly from increased production per unit of resources used. Countries with medium-sized agricultural R&D systems, on the other hand, experienced almost equal contributions to agricultural output growth from both TFP and input growth, averaging 1.4 percent and 1.3 percent per year, respectively.

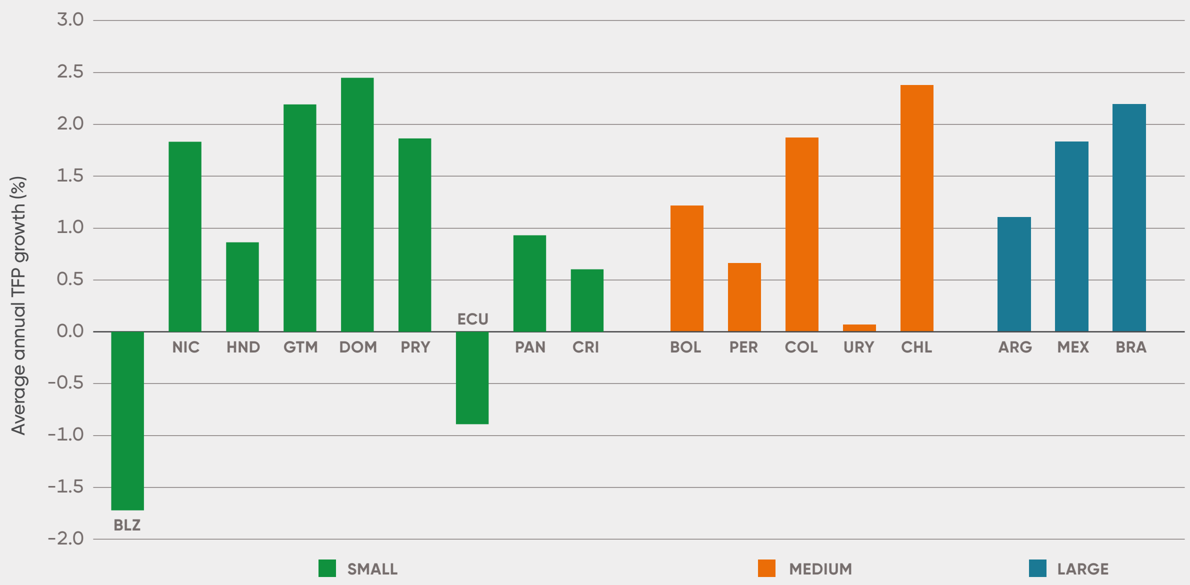
There was significant variation among LAC countries in terms of agricultural TFP growth between 2000 and 2020. The highest rates, exceeding 2 percent per year, were observed in the Dominican Republic, Chile, Brazil, and Guatemala **(Figure 16)**. Following closely were Colombia, Paraguay, Nicaragua, and Mexico, with TFP growth rates ranging from 1.8 to 1.9 percent per year. Bolivia and Argentina recorded lower TFP growth, at only 1.2 percent and 1.1 percent per year, respectively. For the remaining countries, annual TFP growth in Panama, Honduras, Peru, Costa Rica, and Uruguay was below 1 percent. Negative TFP growth rates were observed in Ecuador and Belize.

Figure 15. Growth in agricultural output, TFP, and inputs in LAC broken down by groups of countries with small, medium-sized, and large agricultural research systems, 2000–2020



Source: Estimated by authors based on output and input data from USDA-ERS (2023).

Figure 16. Growth in agricultural TFP in LAC broken down by country, 2000–2020



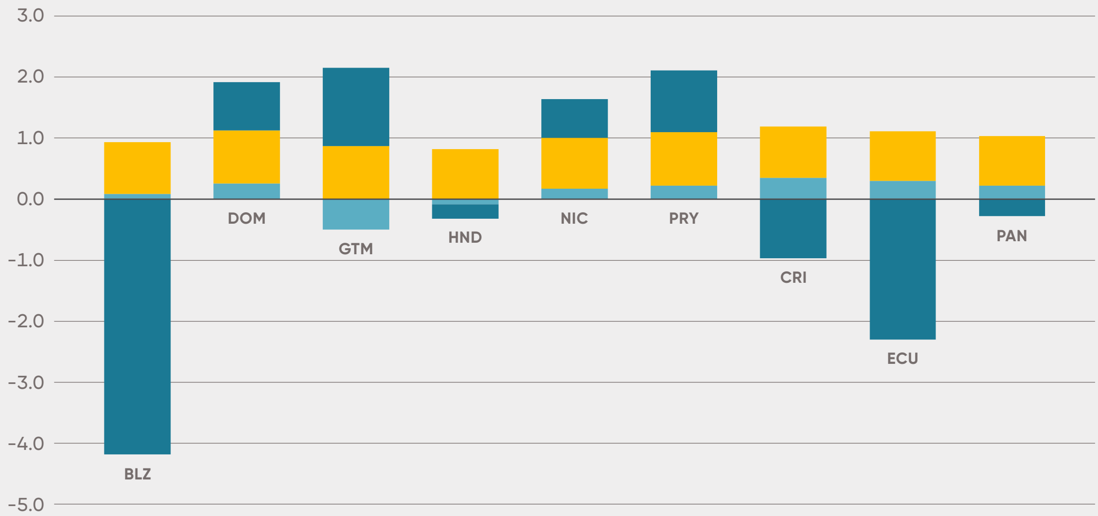
Source: Estimated by authors based on output and input data from USDA-ERS (2023).

To gain a better understanding of the factors driving TFP growth in all these countries, Figure 17 breaks down TFP growth by the contributions of public R&D investment, private R&D investment, spill-ins from abroad, and weather and other shocks. This breakdown reveals that public R&D has provided limited contributions to TFP growth in countries with small agricultural research systems **(Figure 17a)**. During 2000–2020, public R&D contributed to only 0.1 percent annual TFP growth in these countries as a group. This group-wide average, however, masks a significant degree of cross-country variation, with public R&D having contributed relatively more to TFP growth in Costa Rica (0.34 percent per year on average), Ecuador (0.29 percent), and the Dominican Republic (0.25 percent). The model also suggests that private R&D appears to have a limited role in driving TFP growth, which is reflected in the fact that only very few private companies conduct agricultural R&D in these smaller countries. In contrast, spill-ins from abroad were an important factor driving TFP growth in smaller LAC countries, which shows the importance of international knowledge flows in these countries' agricultural productivity. Finally, weather and other shocks also played a considerable role in TFP growth, affecting smaller countries with higher variability.

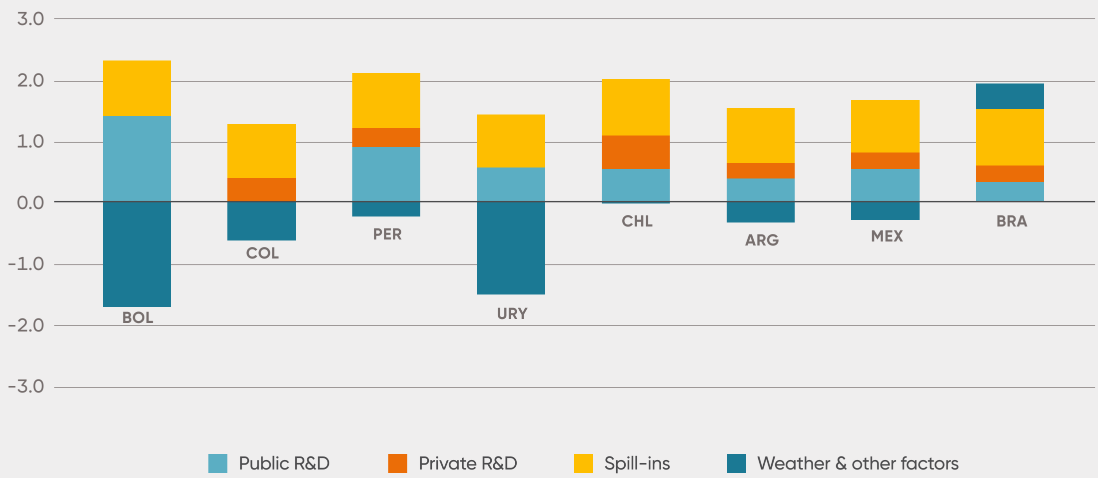
Among countries with medium-sized and large agricultural research systems, on the other hand, the contribution of public R&D investment to TFP growth was much greater, averaging 0.5 percent per year for the group as a whole. Public R&D contributed to an average of 1.27 percent TFP growth per year in Bolivia, followed by Peru (0.81 percent), Uruguay (0.50 percent), Mexico (0.48 percent), and Chile (0.47 percent) **(Figure 9b)**. The impact of private R&D investment on agricultural TFP growth was also much larger in the group of countries with medium-sized and large R&D systems. Overall, private investment contributed an average of 0.23 percent TFP growth annually in these countries during 2000–2020, with the highest contribution seen in Chile (0.51 percent). Spill-ins from abroad played an equally important role in driving TFP growth in countries with medium-sized and large R&D systems than in countries with small systems.

Figure 17. The drivers of agricultural TFP growth in LAC

17a. Countries with small agricultural research systems



17b. Countries with medium-sized and large agricultural research systems



Source: Estimated by authors based on output and input data from USDA-ERS (2023).
Notes: Includes spill-ins from public and private R&D investment in other countries as well as those from R&D investment by CGIAR research centers.

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DISCUSSION AND POLICY IMPLICATIONS

This report provided new insight into the current state and future direction of agricultural R&D in LAC, as well as the structural factors that influence agricultural R&D, innovation capacity, and food system development in the region. The analysis was based on recently updated agricultural research capacity and investment data for ten LAC countries, along with existing agricultural R&D and other datasets for additional countries in the region.

Among the ten countries with updated R&D investment data, there has been a collective increase of 45 percent in agricultural R&D spending between 2007 and 2020. Notably, Bolivia and Peru have played a significant role in driving this growth, thanks to substantial funding from donors and development banks aimed at supporting their agricultural R&D endeavors. These funds have been utilized to implement institutional reforms, train staff, and provide competitive research and innovation grants, resulting in a substantial rise in R&D expenditure. While this increase demonstrates these countries' commitment to agricultural research, the sustainability of these reforms remains uncertain. The ability to maintain current spending levels once the donor and development bank funding concludes will determine the long-term impact of these efforts.

In contrast, investment levels in the remaining eight countries with new data available have largely remained stagnant or declined. This observation aligns with the historical pattern of underinvestment in agricultural R&D across LAC, with only a handful of countries (particularly Brazil) accounting for a significant portion of available agricultural R&D resources. This underinvestment carries serious consequences, including the devaluation of human capital in agricultural research, which hampers the long-term growth of the agricultural sector.

The inadequate state of human capital in agricultural research across LAC countries presents an even more pressing concern than the issue of low R&D investment. The data presented in this report indicates that in most countries, only a small fraction of researchers hold PhD degrees, and of those who do, two-thirds are in their fifties and sixties, nearing the mandatory retirement age. This trend underscores the low priority assigned to agricultural R&D by many countries, leading to a gradual depletion of human capital, the most crucial resource in research, which could take decades to replenish. Furthermore, it highlights the underdeveloped state of agricultural research in many countries, necessitating a comprehensive long-term plan to enhance research capacity and foster the growth of human capital.

The country comparisons in Section 4 emphasize the crucial role of human capital in developing robust research systems. Brazil, Chile, Ecuador, Costa Rica, and Panama have demonstrated superior performance compared to other countries with similar-sized research systems in terms of publications, productivity, and research costs. These disparities can largely be attributed to differences in the quality of human capital and the utilization of capital inputs among these countries.

The analysis in Section 5, which examines the impact of R&D investment on TFP growth, reveals that the success of countries with stronger research systems extends beyond academic outcomes alone. Among the ten countries analyzed with updated data, public R&D has played a relatively greater role in contributing to TFP growth in Costa Rica, Ecuador, Bolivia, and Peru. Three of these four countries have made significant strides in increasing R&D investment and investment in human capital in recent years. Furthermore, Costa Rica has successfully developed one of the strongest research systems among LAC countries with smaller research capacities. Overall, the data indicate that countries with small research systems have experienced slower TFP growth over time compared to those with larger or medium-sized systems, posing a challenge for the future development of research in these countries.

This raises the important question:

Why do countries in the region continue to underinvest in R&D, despite historical evidence pointing to high returns on such investments?

There is no definitive answer to this question, but a decade ago, Trigo et al. (2013) proposed a set of hypotheses aiming to answer this question and offered recommendations for revitalizing research systems in LAC that remain valid today. Drawing from the analysis of Trigo et al. (2013), we highlight several key elements below that help explain the insufficient investment in R&D in the region.

The current state of the INIA model, which played a pivotal role in the agricultural technological transformations of the region in its initial decades, is now subject to significant scrutiny. This is evident in its diminished political significance, resulting in reduced financial support and a lack of rejuvenation in the cadre of qualified researchers. Various factors contribute to the lack of support for agricultural research in the region.

In the first place, the creation of the INIAs as semi-autonomous public research institutes occurred several decades ago when the agrifood sector was less developed, with primary production accounting for the majority of the system's value. In this context, R&D priorities focused on addressing production issues and improving natural resource management, while post-harvest and agro-industrialization stages were not yet regarded as high priorities.

The food production chain in LAC has undergone significant transformations since the establishment of the INIAs. Rising incomes and urbanization have resulted in shifts in food consumption patterns, demanding higher quality and a wider variety of products. This, in turn, has influenced technological advancements in primary production and investment in non-agricultural segments of the food chain. Consequently, national markets have experienced greater integration of input and output markets, leading to an expanded and more diverse food chain with closer connections between primary production, food processing industries, and the retail sector.

These changes in the food chain have diminished the political and institutional significance of the INIAs. It is now widely recognized that agricultural research involves multiple actors, both public and private, without a single governing entity. Innovation emerges through the collaboration and integration of knowledge and efforts from various sources, including universities, private research centers, companies, NGOs, and even the active involvement of producers themselves. In this context, the private sector has assumed a strategic role in driving innovation, especially in the commercialization of technologies, as many new ideas and concepts are market-oriented and require the involvement of companies to reach the market.

Consequently, the food chain has undergone a significant transformation, placing a greater emphasis on value addition through processing and marketing. This shift has led to increased participation of firms in the value chain and a relative decline in the primary sector. Thus, while public research remains important in the domain of "public goods", agricultural innovation now occurs in a more diverse and complex context, where collaboration and knowledge sharing are key to achieving significant progress.

Another contributing factor to the declining significance of the INIAs is the scientific progress in non-agricultural areas that have implications for agricultural research. Many INIAs are not adequately prepared, both organizationally and institutionally, to incorporate the advances in new biotechnologies and information and communication technologies (ICT). For example, genome editing technologies in crops, animals, and microorganisms, as well as digital innovations that assist farmers, traders, and policymakers in making informed decisions along value chains, require fundamental changes in human resource development and stronger collaboration between INIAs and research centers in universities, public institutes, industries, and emerging actors such as telecommunications companies and software developers (Benfica et al., 2023).

Therefore, the INIA model has become outdated both in terms of scientific advancements and operational effectiveness. The emerging scenarios necessitate a broader research agenda, addressing issues related to shifting food demand, the development of the agrifood system, and changes in the scientific landscape of agricultural research. Adaptations to new realities require institutional changes to revitalize the INIAs. It is within this context that the concept of national agricultural innovation systems emerges, offering opportunities to incorporate new actors into the process and facilitate the interaction between biological sciences and other knowledge domains in innovation processes.

These innovation systems are defined as networks comprising agents directly or indirectly involved in the introduction and dissemination of new products and technological processes. This concept is rooted in the notion that society's interest in investing in the generation of new knowledge and technologies goes beyond their intrinsic value alone. It is driven by the recognition that their application in the innovation process can contribute to the greater well-being of society. While this concept is still evolving, with ongoing conceptual debate about its implications, little progress has been made in LAC regarding concrete policies and implementation (World Bank, 2011). **Therefore, LAC countries must address fundamental questions to drive the transformation of agricultural research and innovation systems.**

Firstly, it is imperative to ascertain the most effective approach for connecting research and innovation processes. This entails identifying innovative solutions that have the potential to address the multiple challenges faced by food systems in the region. Additionally, understanding the role that research can play in the development of these innovations, determining the required policies and institutions to promote innovation and defining the actors and their respective responsibilities within the innovation process are essential.

Secondly, it is crucial to foster the integration of INIAs into national science, technology, and innovation systems. While these institutions have played an important role in the past, they have often operated in relative isolation from other scientific and technological entities, possibly due to their historical circumstances. It is therefore essential to provide them with the necessary support to effectively integrate into these systems and establish closer links with other scientific and technological institutions.

Thirdly, advancing alliances between research systems of different countries, both within and outside the region, is crucial. This is particularly important for countries with relatively less developed research systems and small economies that face limitations in building institutions of sufficient size to tackle the diverse range of challenges and services they encounter. These countries face greater difficulties in areas such as the growing importance of basic research in innovation processes and the internationalization of frameworks for the protection of intellectual property rights of new technologies, posing greater difficulties for their research development into the future (Benfica et al., 2023). Therefore, building strong cooperation networks with regional public R&D and agricultural extension systems, as well as with the private sector, becomes essential in achieving greater efficiencies. National systems should actively collaborate with their regional counterparts, including regional cooperation mechanisms, the Tropical Agricultural Research and Higher Education Center (CATIE), and CGIAR centers located in the region such as CIMMYT, CIAT, and CIP, in addition to research centers and universities outside the region. This strategic approach is crucial for catching up with the knowledge frontier and optimizing resource utilization by avoiding duplication of efforts, which holds particular relevance for smaller countries where investment constraints are more significant.

Fourthly, the development and implementation of new biotechnology require addressing regulatory gaps that hinder stakeholders from safely developing, implementing, and utilizing bio-innovations and digital technologies. This includes addressing intellectual property issues related to access to and management of innovations, as well as regulatory considerations to minimize the cost of delays in development, deployment, and adoption processes. Streamlining regulatory frameworks in these areas is essential to foster innovation and ensure efficient progress (Benfica et al., 2023).

Finally, countries with small and/or least developed research systems must address important gaps in their investments in research and development, as well as in institutional and human capacities. This is crucial for enhancing the quality, scope, and potential of their research systems and narrowing the scientific gap that separates them from the most advanced countries in the region. Achieving this goal requires strengthening coordination between national institutions and those of other countries, fostering collaboration around shared objectives, and prioritizing the training of a new generation of scientists with the necessary skills to generate and deliver the required innovations.

Another crucial aspect in strengthening research in the region is the establishment of effective financing mechanisms. Traditional institutional funding, characterized by unrestricted government or donor funding of public research, has gradually diminished in importance in OECD countries. Instead, performance-based criteria have been introduced, whereby funds are allocated to institutions based on their research excellence through a peer review process and periodic evaluation exercises. Adopting similar approaches in LAC can help allocate resources more strategically and promote a culture of excellence in research institutions.

In the context of LAC, it is evident that a new institutional framework that prioritizes innovation will require the adoption of more flexible and competitive funding systems. These systems should address priority issues set by governments or research councils and employ performance-based approaches to institutional financing. Countries that have already implemented such changes commonly cite various reasons for doing so. These include enhancing the quality of research, fostering interdisciplinary research, overcoming institutional and structural constraints, facilitating networking among different institutions, and promoting the development of young researchers. By embracing these approaches, LAC can create a conducive environment for innovation and research advancement. The region already has a notable precedent in the Regional Fund for Agricultural Technology (FONTAGRO), which is a sustainable regional co-financing mechanism established in 1998. It focuses on the development of agricultural technology in Latin America, the Caribbean, and Spain with the aim of promoting the sustainable management of natural resources. FONTAGRO plays a significant role as a cooperation mechanism for R&D among member countries, fostering the creation of technologies and innovations relevant to their societies. To shape the future of research and innovation institutions in the region, it will be necessary to establish similar initiatives at both regional and national levels.

In the emerging national research and innovation systems, the private sector will assume a leading role in addressing many of the long-standing concerns of public systems. However, the public agricultural research system will continue to hold a crucial position in the region. Certain "public goods" inherently lack attention from other actors in the innovation system, including climate mitigation and adaptation, territorial development, diversification of production, and biodiversity. Within this context, public research institutions should capitalize on the opportunity to align their research agenda with these vital "public goods" that are essential for development, but may not attract interest from other actors in the innovation system.

In summary, achieving a thriving agri-food sector in LAC hinges upon the adoption of the recommendations outlined in this discussion as well as a forward-looking mindset. Nurturing research and innovation, making strategic investments, and fostering cross-border and cross-sector collaboration are vital actions to take. By doing so, LAC can unleash its untapped potential and emerge as a frontrunner in sustainable agricultural development on the global stage. To embark on this transformative journey towards a prosperous and resilient future for agriculture in LAC, it requires the concerted efforts and unwavering determination of all stakeholders. Together, they can forge a path towards a brighter tomorrow for the region. The time for action is now.

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ANNEX A. FOOD SYSTEMS AND INNOVATION

A.1. THE FOOD SYSTEM

A.1.1. Factors Driving Transformation of Food Systems

Meta-conditioners

Reardon (2019) identifies three crucial meta-factors behind food systems (FS) development.

- A first crucial pull factor is growth in income and population. Income growth and increasing opportunity cost of time as women work outside the home in urban and rural areas lead to diet and shopping changes.
- Second, policy liberalization and privatization leads to a minimization of the government's direct role in food systems, with the private sector stepping in to replace the government, incentivized by the development of urban markets.
- The third key meta-conditioner of food system development is infrastructure, which reduces transaction costs and forms the foundation for food supply chain development from rural areas to cities and towns.

Urbanization

Growing urbanization transforms food systems from short and local supply chains serving villages and nearby towns to long and national (or international) supply chains where production can be located far from consumption centers.

Diet change

Three main changes occur in diets and the final destination of foods.

- First, as income rises, there is a shift toward a higher proportion of non-staples in the diet. This implies disproportional growth of the production chains of non-staples (vegetables and fruits, meat, fish, dairy, and edible oils).
- Second, with the development of food systems, the diet shifts towards processed and purchased products.
- Finally, with a growing demand for livestock products, there is a rapid increase in the demand for cereals as feed grains.

A.1.2. Transformation and Structure of Food Systems

According to Reardon (2019), the transformation of food systems occurs over three stages of structural change.

- Traditional system—Spatially short (local) and fragmented, using technologies with little capital and much labor, with no contracts or formal standards, and spot markets linking all segments.
- Transitional system—Spatially long as cities grow, and their catchment area becomes larger and larger, but still fragmented. Chain actors use a mix of capital-intensive and labor-intensive technologies, and there is an emerging demand

for public standards of quality, but spot market relations still dominate.

- Modern system—Spatially long in all levels of the value chain, there is an emergence of quality standards and contracts and capital intensification is common as the modern system normally coincides with higher wages in the economy and more quality and safety control are demanded by the food industry.

There are several dimensions to the structural transformation of food systems. Reardon highlights a) expansion, which implies exponential growth of the size of the food system with development; b) elongation, which Reardon defines as the growth of rural-to-urban food supply chains and growth of rural-to-rural and urban-to-urban chains.

Change in industrial organization structure:

a) Increase in the post-farmgate segments
b) Emergence of small off-farm food system enterprises
c) Concentration and dis-intermediation

Change in conduct:

a) Endogenous transfer of technologies produced in other countries.
b) Focus on farm technologies, from breeding and management to those that link product cycle, breeding, and commoditization.
c) Non-seed inputs to support farming intensification.
d) Post-farmgate technology change results from an increase in wage rates and cheaper capital inducing midstream and downstream capital intensification and productive capital upgrading.
e) Logistic innovations: processing scale and clustering innovations; freezing and packaging innovations; safety monitoring.

Detailed information on the data and indices used to build the FSDI are presented in **Table A.1.**

Table A.1. Components of the Food System Development Index (FSDI)

Indicator	Variable name	Definition	Source	Period
FOOD SYSTEM DEVELOPMENT INDEX	**FSDI**	**FSDI = (Idiet + Isupply)*0.5**		
DIET	**Idiet**	**Idiet = (Diet_div + Prot_animal)*0.5**		
Diet diversification	**Diet_div**	A measure of the share of non-starchy foods (all foods other than cereals, roots and tubers) in total dietary energy consumption	**FAO (2022)**	**2011-2016**
Consumption of animal protein	**Prot_animal**	Supply of animal protein for human consumption (grs/person/year)	**FAO (2022)**	**2011-2016**
SUPPLY	**Isupply**	**Isupply = (Ikintens + Ivchain)*0.5**		
Capital intensity, farm level	**Ikintens**	Ikintens= 0.07*ln(Fert_wk)+0.001*ln(Ph_wk)+0.41*ln(Feed_wk)+0.21*ln(Mach_wk)+0.3*ln(Irri_wk). Weights to add up the individual input intensity values are obtained from regressing labor productivity against individual intensities and animal stock and land per worker. Animal stock and land per worker is not included in the index	**USDA-ERS (2022)**	**2011-2016**
• Fertilizer/worker	**Fert_wk**	Metric tonnes of N, P2O5, K2O fertilizer consumption	**USDA-ERS (2022)**	**2011-2016**
• Pesticides and herbicides/worker	**Ph_wk**	Quantities (in tonnes of active ingredients) of pesticides used in or sold to the agricultural sector for crops and seeds	**USDA-ERS (2022)**	**2011-2016**
• Machinery/worker	**Mach_wk**	The total stock of farm machinery in "40-CV tractor equivalents" (CV=metric horsepower), aggregating the number of 2-wheel tractors, 4-wheel tractors, and combine-harvesters and threshers	**USDA-ERS (2022)**	**2011-2016**
• Irrigated area/worker	**Irri_wk**	Area equipped for irrigation	**FAO (2022)**	**2011-2016**
• Animal feed/worker	**Feed_wk**	Total metabolizable energy (ME) in animal feed from all sources, in 1000 Mcal (Mcal=megacalories)	**USDA-ERS (2022)**	**2011-2016**
Value chain development	**Ivchain**	Ivchain = (Qsupplier + Cluster + Vchbreadth + Psophistication + Marketing + Grocery)*(1/6)		
• Quality of local supplier	**Qsupplier**	[1 = extremely poor quality; 7 = extremely high quality]	**Schwab (2018)**	**2011-2014**
• State of cluster development	**Cluster**	Development and depth of clusters (geographic concentration of firms, suppliers, producers of related products and services, and specialized institutions in a particular field). [1 = nonexistent; 7 = widespread in many fields]	**Schwab (2018)**	**2011-2014**
• Value chain breadth	**Vchbreadth**	Presence of companies in the value chain [1 = narrow, primarily involved in individual steps of the value chain (e.g., resource extraction or production); 7 broad, present across the entire value chain (e.g., including production, marketing, distribution, design, etc.)]	**Schwab (2018)**	**2011-2014**
• Production process sophistication	**Psophistication**	[1 = not at all—production uses labor-intensive processes; 7 = highly—production uses latest technologies]	**Schwab (2018)**	**2011-2014**
• Extent of marketing	**Marketing**	Success of companies in using marketing to differentiate their products [1= not successful at all; 7 = extremely successful]	**Schwab (2018)**	**2011-2014**
• Presence of formal grocery sector	**Grocery**	[0 = Minimal presence, 1 = Moderate presence, 2 = Widespread presence]	**Schwab (2018)**	**2011-2014**

Source: Nin-Pratt and Stads (2023).

A.2. THE INNOVATION SYSTEM

The approach to analyzing innovation encompasses not only science suppliers but extends to factors affecting demand for and use of knowledge, as noted by the World Bank (2006). Spielman and Birner (2008) propose a conceptual framework of the Agricultural Innovation System (AIS), which captures its essential elements, the linkages between its components, and the institutions and policies that constitute the enabling environment for innovation. These essential elements are:

A. The knowledge and education domain, composed of agricultural research and education systems.

B. The business and enterprise domain, which includes the set of value chain actors and activities that both use outputs from the knowledge and education domain and innovate independently.

C. Bridging institutions, which link the two domains, including extension services, political channels, and stakeholder platforms that facilitate the transfer of knowledge and information between domains.

D. Context conditions that foster or impede innovation, including public policies on innovation and agriculture and informal institutions that condition how individuals and organizations within each domain act and interact.

The innovation index used in this study was built based on these essential elements. **Table A.2.** presents details on the index and its sources.

Table A.2. Index of Innovation Capacity (IIC) and its components

Indicator	Variable name	Definition	Original values	Source	Period
INDEX OF INNOVATION CAPACITY	**IIC**	**IIC = (Ihcapital+Iresearch+ Ienvironment+Ipolicy+Iinstitutions)*(1/5)**			
HUMAN CAPITAL	**Ihcapital**	**Ihcapital = 0.62*Ienrol+0.38*Ieduqual**			
Enrollment	**Ienrol**	Ienrol = (Prim+Sec+Ter+Ysch)*(1/4)			
• Primary education	**Prim**	Gross enrollment ratio is the ratio of total enrollment, regardless of age, to the population of the age group that officially corresponds to the level of education shown	Value	**World Bank (2022)**	**2011-2016**
• Secondary education	**Sec**				
• Tertiary education	**Ter**				
• Years of schooling	**Ysch**	Average number of years people aged 25+ participated in formal education	Value	**Barro & Lee**	**2010**
Quality of education	**Iqedu**	Iqedu = (Qmath + Qprim + Qedu)*(1/3)		**Schwab (2019)**	**2011-2014**
• Quality of math education	**Qmath**	Quality of math and science education	[1 = extremely poor—among the worst in the world; 7 = excellent—among the best in the world]	**Schwab (2019)**	**2011-2014**
• Quality of primary education	**Qprim**	Quality of primary education		**Schwab (2019)**	**2011-2014**
• Quality of education	**Qedu**	Degree on which the education system meets the needs of a competitive economy	[1 = not well at all; 7 =extremely well]	**Schwab (2019)**	**2011-2014**
RESEARCH	**Iresearch**	**Iresearch = (UI+ SCIpapers+Hbio+Hcomp+Heng)*(1/5)**			
• University-industry collaboration	**UI**	University-industry collaboration in Research & Development	1-7 Best	**Schwab (2019)**	**2011-2014**
• Scientific papers	**SCIpapers**	Number of publications in biochemistry, genetics, molecular biology, computer science and engineering per person enrolled in tertiary education	Value		
• Quality of publications in biochemistry, genetics and molecular biology	**Hbio**	H index biochemistry, genetics, and molecular biology	Value		
• Quality of publications in computer science	**Hcomp**	H index computer science	Value		
• Quality of publications in engineering	**Heng**	H index engineering	Value		

Source: Nin-Pratt & Stads (2023).

Table A.2. Index of Innovation Capacity (IIC) and its components (continued)

Indicator	Variable name	Definition	Original values	Source	Period
INNOVATION ENVIRONMENT	**Ienvironment**	**Ienvironment = 0.87*Iinvenv+0.13*Iopen**			
Investment environment	Iinvenv				
Openness	Iopen				
• Local competition	IE_1	The intensity of local competition	1-7 Best	Schwab (2019)	2011-2016
• Scientists and engineers	IE_2	Availability of scientists and engineers	1-7 Best		
• Capacity to attract talent	IE_3	Country capacity to attract talent, 1-7 (best)	1-7 Best		
• Capacity to retain talent	IE_4	Country capacity to retain talent, 1-7 (best)	1-7 Best		
• Staff training by business	IE_5	Extent of staff training, 1-7 (best)	1-7 Best		
• Finance affordability	IE_6	Affordability of financial services, 1-7 (best)	1-7 Best	Schwab (2019	2011-2016
• Access to loans	IE_7	Ease of access to loans, 1-7 (best)	1-7 Best		
• Venture capital	IE_8	Venture capital availability, 1-7 (best)	1-7 Best		
• Availability of training	IE_9	Availability of research and training services, 1-7 (best)	1-7 Best		
• Imports	IE_10	Imports as a percentage of GDP	Value		
• R&D investment	IE_11	Current and capital expenditures (both public and private) on research and development (R&D), expressed as a percentage of GDP. Covers basic research, applied research and experimental development.	Value	World Bank (2022)	2011-2016
INNOVATION POLICY	**Ipolicy**	**Ipolicy = 0.81*Apc1 + 0.19*Apc2**			
• Intellectual property	IP_1	Intellectual property protection, 1-7 (best)	1-7 Best	Schwab (2019)	2011-2016
• Taxes and investment	IP_2	Effect of taxation on incentives to invest	1-7 Best		
• Investor protection	IP_3	Strength of investor protection	0-10 Best		
• FDI tech	IP_4	Foreign direct investment and technology transfer	1-7 Best		

Source: Nin-Pratt & Stads (2023).

Table A.2. Index of Innovation Capacity (IIC) and its components (continued)

Indicator	Variable name	Definition	Original values	Source	Period
• FDI rules	IP_5	Business impact of rules on FDI	1-7 Best	Schwab (2019)	2011-2016
• Property rights	IP_6	Property rights (WEF)	1-7 Best		
• Number of days to start a business	IP_7	Number of days to start a business	Value		
• Government regulation	IP_8	Burden of government regulation, 1-7 (best)	1-7 Best		
QUALITY OF INSTITUTIONS	**Iinstitutions**	**Iinstitutions = (0.89*Icorrupt+011*Icrime)**			
Corruption	**Icorrupt**	Icorrupt=First principal component of QI1-QI13			
Crime	**Icrime**	Icrime=Second principal component of QI1-QI13			
• Bribes	QI1	Irregular payments and bribes, 1-7 (best)	1-7 Best	Schwab (2019)	2011-2014
• Independence of justice	QI2	Judicial independence, 1-7 (best)	1-7 Best		
• Legal 1	QI3	Efficiency of legal framework in challenging regs., 1-7 (best)	1-7 Best		
• Legal 2	QI4	Efficiency of legal framework in settling disputes, 1-7 (best)	1-7 Best		
• Policy	QI5	Transparency of government policymaking, 1-7 (best)	1-7 Best		
• Government favoritism	QI6	Favoritism in decisions of government officials, 1-7 (best)	1-7 Best		
• Strength of audit	QI7	Strength of auditing and reporting standards, 1-7 (best)	1-7 Best		
• Police reliability	QI8	Reliability of police services	1-7 Best		
• Customs burden	QI9	Burden of customs procedures	1-7 Best		
• Cost of crime	QI10	Business costs of crime and violence	1-7 Best		
• Cost of terrorism	QI11	Business costs of terrorism	1-7 Best		
• Organized crime	QI12	Organized crime	1-7 Best		
• Trust in politicians	QI13	Public trust in politicians	1-7 Best		

Source: Nin-Pratt & Stads (2023).

ANNEX B. INDICATORS FOR THE ANALYSIS OF THE PERFORMANCE OF RESEARCH SYSTEMS

To assess the overall performance of national agricultural R&D systems across LAC, the analysis in this section relies on two main data sources:

1. Data from IFPRI's ASTI database (2023)

Provide detailed information on the institutional structure, capacity, expenditures, and funding structure of agricultural research systems. ASTI has recently updated its datasets to the year 2020 for ten countries in LAC (Belize, Bolivia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Honduras, Nicaragua, Panama, and Peru) with IDB support (see Section 3). The available ASTI data for the remaining LAC countries only covers the period up to 2013. In order to estimate the agricultural R&D investment levels of these countries in more recent years, extrapolations were made based on the annual growth rates of these countries' agricultural GDP.

2. Data from SCImago (2023)

Provide detailed information on the total number and quality of publications in agricultural and biological science aggregated at the country level to represent the direct research output.

Based on these two data sources, the following variables and indicators were selected and compiled to provide a comprehensive understanding of research system performance.

- **Number of published articles:** The number of articles published in agricultural and biological sciences (SCImago, 2023) and the H index—an indicator of quantity and quality of publications (Hirsch, 2005) —are used as measures of scientific output. These variables provide insights into the development of agricultural science, the research system in the country, and the degree of integration with the global scientific community in this field.[5]
- **R&D expenditure per publication:** This indicator links the scientific output of research systems with the costs incurred to generate those research outputs. Its value depends on the productivity of researchers and on the cost per researcher. Costs of the research system are obtained from ASTI and used in combination with the output measure described above to calculate the research cost per unit of output for each country.

5. The scientific production of research systems is often measured by the number of published articles. However, this is only one type of research output, with others including new crop varieties, improved livestock breeds, new inputs, and intangibles such as new processes and more efficient resource allocation. Unfortunately, data on these other research outputs are not available for country comparisons at this level. Nevertheless, it is generally assumed that published articles are a by-product of research on new technologies, and therefore serve as a reflection of the productivity and quality of research being conducted in a country. Given this assumption, the authors concluded that bibliographies of scientific publications in agricultural and biological science are the most dependable source of information for comparing research outputs and processes across countries. To develop a quality-adjusted measure of research output, the authors used data on the number of publications and their "h-index" from SCImago (2023). As a result, they were able to produce a quality-adjusted measure of research output for scientific articles published in the fields of agriculture and biology.

- **Cost and output per researcher:** R&D expenditure per publication can be decomposed into cost per full-time equivalent (FTE) researcher and the number of publications per FTE researcher, a measure of productivity. The more productive researchers are, the lower the cost per publication. Higher spending per researcher increases the cost of publications, but it also results in higher productivity. This means that higher costs per researcher could reduce cost per unit of output if growth in productivity compensates for increases in the cost per researcher.

- **Cost structure:** ASTI's research expenditure data can be broken down by salary costs, operating costs, and capital investments. The cost structure of research is analyzed using two indicators: the share of each of the three cost categories in total R&D costs, and the ratios between the values of each of the three cost categories.

- **Size of the agricultural R&D system:** Two variables are used to represent the size of the system in a country: a) Average R&D spending and b) Total number of FTE researchers in agriculture. These variables provide insights into the scale of a country's research system and the resources available for agricultural research.

- **Institutional composition of public agricultural research:** The indicators in this group illustrate how a country's R&D spending is distributed among government research agencies, higher education agencies, and non-profit organizations, providing valuable insights into the public sector's role in supporting agricultural research.

ANNEX C. PRODUCTION, PRODUCTIVITY, AND R&D

C.1. PRODUCTION MODEL

The production and productivity analysis adopts a representation of the standard log-linearized Cobb–Douglas production-function model. We discuss all its features in detail below. Formally, for time periods $t = 1, \ldots, T$, countries $i = 1, \ldots, I$, and inputs $n = 1, \ldots, N$, let y_t and x_{nt} be the log of agricultural output and input *n*, respectively. Total agricultural output in year *t* expressed in logs results from adding up total input and unobserved TFP (tfp_{it}), where β_{in} is the output elasticity of input *n in country i.*

C.1 $$y_{it} = tfp_{it} + \sum_n \beta_{in} x_{int}$$

As in Griliches (1979), TFP is assumed to be a function of past levels of R&D expenditure and several other factors (climate, market shocks, policies, etc.) included in μ_{it}.

C.2 $$tfp_{it} = \alpha_{i0} + \alpha_i ln[\sum_{s=1} \omega_{it-s} RD_{it-s}] + \mu_{it}$$

The parameter α_{io} represents the level of TFP in country *i* that results from fixed factors specific for country i, while ω_{it-s} represents the fraction of R&D invested in period *t-s* that contributes to TFP in period *t*. For example, ω_{it-s} could be reflecting the depreciation of total R&D invested in *t-s* between *t-s* and *t*. We define the knowledge stock of country *i* as the weighted sum of all past R&D investments, the term in parenthesis in Eq. C.2., with α_i being the fraction of the knowledge stock that contributes to the level of TFP, or in terms of change, it is the R&D elasticity or the change in TFP that results from a 1 percent increase in the knowledge stock.

C.3 $$tfp_{it} = \alpha_{i0} + \alpha_i KS_{it} + \mu_{it}$$

If the knowledge capital discussed so far (KS) is the result of public R&D investment, the same idea applies to private R&D, so private R&D investment in country i results in private knowledge stock. Furthermore, direct R&D investment (public and private) is not the only source of knowledge available to a country. The process of knowledge transmission from one actor to another without deliberate action is referred to as `knowledge spillovers.' The knowledge produced by country j is assumed to be partially available to country i as a function of the 'distance' between the two countries. In the case of agriculture, the smaller the difference in climate, agroecologies and in production systems and technology, the smaller the 'distance' between the two countries. Geographic distance is also considered, meaning that the shorter the geographic distance between countries, the more likely is for these countries to receive knowledge spill-ins from each other. Finally, TFP is not only driven by the accumulation of knowledge stocks from different origins but is also affected by other factors like climate, market shocks, innovations not generated by research, policies, and investments that improve the economic environment for agriculture, among others. Decomposing the term μ_{it} in Eq. (B.3) to explicitly represent these drivers results in Eq. (C.4).

C.4 $$tfp_{it} = \alpha_{0i} + \alpha_i^{pb} KS_{it}^{pb} + \alpha_i^{pv} KS_{it}^{pv} + \alpha_i^{sp} SP_{it} + \sum_f \gamma_{if} W_{if} + \varphi_{it}$$

Where W_f are weather variables with *f={precipitation, temperature}*, and *KS* represents the knowledge stock and *pb* and *pv* refer to public and private knowledge stocks and their respective elasticities while KS^{sp} is the knowledge stock that results from knowledge spill-ins from other countries shown in Eq. (C.5).

C.5 $$SP_{it} = \sum_{j \neq i} d_{ij} KS_{jt}$$

In Eq. (C.5) KS_{jt} represents the knowledge stock of country *j* and d_{ij} is the distance between countries *i* and *j*. In this case, SP_{it} is a generic term to represent all spill-ins to country *i,* but this could be further decomposed into spill-ins to *i* from the public ($SPpb_{it}$) and private investment ($SPpv_{it}$) in other countries, and spill-ins from R&D investment by international research centers ($SPcg_{it}$).

C.2. CALIBRATION

In this study, we are primarily interested in measuring the impact of a country's public agricultural R&D investment on TFP growth and separating these effects from those of public and private spillovers from other countries and spillovers from international research centers (CGIAR). To do this we calibrate the production model depicted by Eq. (C.1) and (C.5) to track the historical production record of 92 countries over the period 1991-2020. Observable historical variables are total agricultural output and inputs (USDA-ERS, 2023), public R&D investment from ASTI (2022), and private R&D investment from Fuglie (2016), together with partial historical information on output and R&D elasticities.

The model is calibrated to replicate historical agricultural production by estimating the elasticity parameters using a Maximum Entropy (ME) approach (see for example Arndt et al., 2002). This approach allows one to use all available data, and prior information about parameter values and introduce all relevant constraints to better replicate past performance but does not assume any information we do not have. A compact version of the model to be calibrated is as follows.

C.6 $$y_{it} = \sum_n \beta_{in} x_{int} + \alpha_{0i} + \alpha_i SRD_{it} + \sum_f \gamma_{if} W_{if} + \sum_h \tau_{ih} F_{ih} + \varepsilon_{it}$$

Where SRD represents all R&D stocks (own public and private investment and knowledge spill-in stocks), x_{int} and W_{if} are inputs and weather variables respectively, and F_{ih} represents other factors affecting production. Each of the unknown parameters for which we have a priori information (β_{in}, α_i) are treated as discrete random variables expressed as:

C.7 $$\beta_{in} = \pi_{ink}^{\beta} z_{ink}^{\beta} + \epsilon_{ink}^{\beta}$$

C.8 $$\alpha_{ik} = \pi_{ik}^{\alpha} z_{ik}^{\alpha} + \epsilon_{ik}^{\alpha}$$

where the z_{ink}^{β} and z_{ik}^{α} represent the range of values k that β and α can take based on a priori information, and π_{ink}^{β} and π_{ik}^{α} are the respective probabilities of occurrence of those values (must be non-negative and sum to one). Similarly, each error term $\left(\varepsilon_{it}, \epsilon_{ink}^{\beta}, \epsilon_{ik}^{\alpha}\right)$ is treated as a finite and discrete random variable with their respective probability of outcome $\left(\pi_{ik}^{\varepsilon}, \pi_{ink}^{\epsilon\beta}, \pi_{ik}^{\epsilon\alpha}\right)$. Each of the π probabilities are estimated while a priori values of those probabilities $\left(P_{ik}^{\varepsilon}, P_{ink}^{\epsilon\beta}, P_{ik}^{\epsilon\alpha}\right)$ are used for the estimation together with their respective support values. Parameters of weather and F variables in Eq. (C.6) (γ_{if}, τ_{ih}) are estimated without the imposition of a prior distribution. Supports z are specified with five points, supporting recovery of information about higher moments of the distribution.

The problem is solved to minimize the divergence between the prior distribution and the desired distribution subject to the production function and constraints with expected probabilities and support values as explained above. **Figure C.1.** shows observed and estimated values of output for the 17 LAC countries included in the analysis.

C.9

$$minimize\ CE_i = \sum_n \sum_k \pi_{ik}^{\beta} \times ln\left(\frac{\pi_{ik}^{\beta}}{P_{ink}^{\beta}}\right) + \sum_m \sum_k \pi_{itk}^{\varepsilon} \times ln\left(\frac{\pi_{itk}^{\varepsilon}}{P_{itk}^{\varepsilon}}\right) + \sum_m \sum_k \pi_{imk}^{\alpha} \times ln(\pi_{imk}^{\alpha})$$

$$y_{it} = \sum_n \beta_{in} x_{int} + \alpha_{0i} + \alpha_i SRD_{it} + \sum_f \gamma_{if} W_{if} + \sum_h \tau_{ih} F_{ih} + \varepsilon_{it}$$

$$\varepsilon_{it} = \sum_k \pi_{ik}^{\varepsilon} z_{ikt}^{\varepsilon} - \sum_k P_{ik}^{\varepsilon} z_{ikt}^{\varepsilon}$$

$$\beta_{in} = \pi_{ink}^{\beta} z_{ink}^{\beta} + \epsilon_{ink}^{\beta}$$

$$\epsilon_{ink}^{\beta} = \Sigma_k \pi_{ink}^{\beta} z_{ink}^{\beta} - \Sigma_k P_{ink}^{\beta} z_{ink}^{\beta}$$

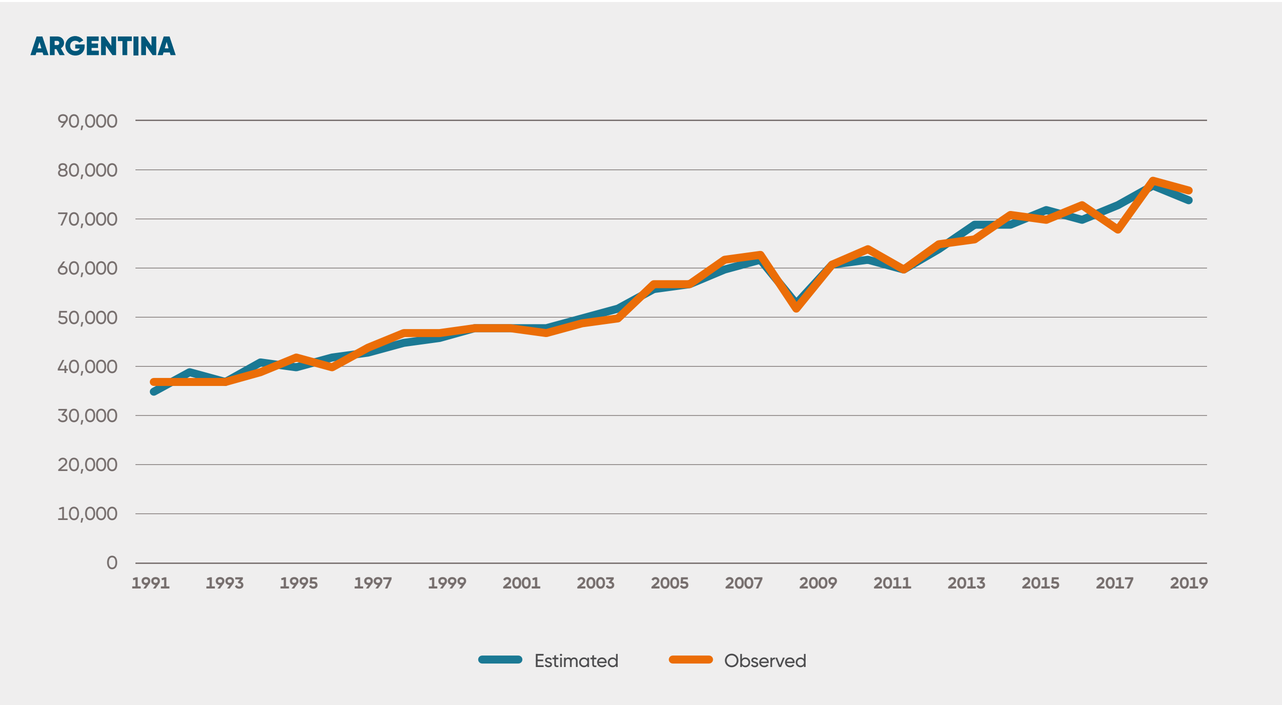
$$\sum_n \beta_{in} = 1$$

$$\alpha_{ik} = \pi_{ik}^{\alpha} z_{ik}^{\alpha} + \epsilon_{ik}^{\alpha}$$

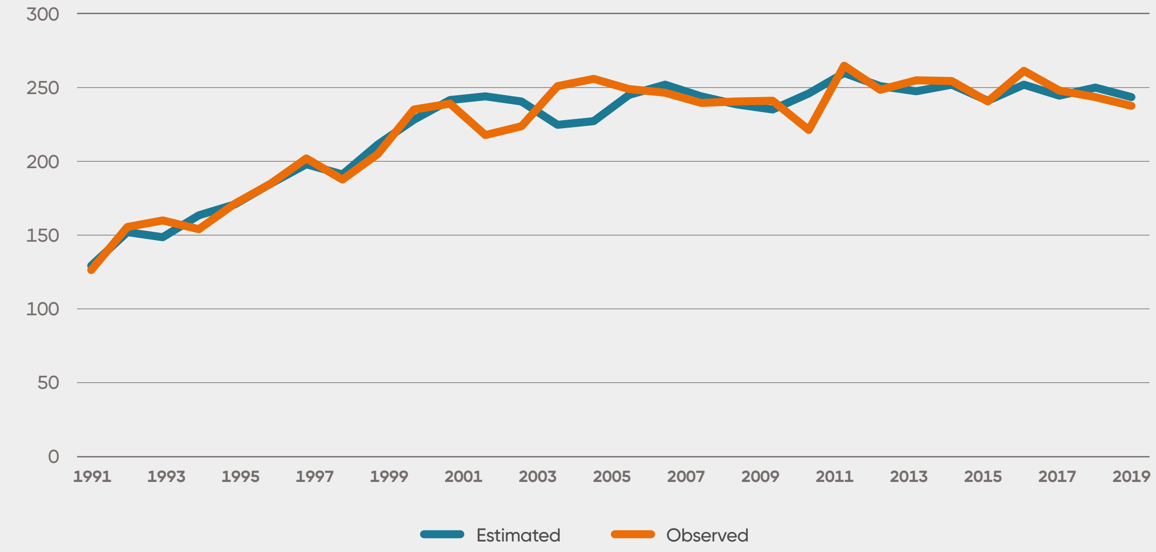
$$\epsilon_{ik}^{\alpha} = \sum_k \pi_{ik}^{\alpha} z_{ik}^{\alpha} - \sum_k P_{ik}^{\alpha} z_{ik}^{\alpha}$$

$$\sum_k \pi_{ik}^{\alpha} = 1$$

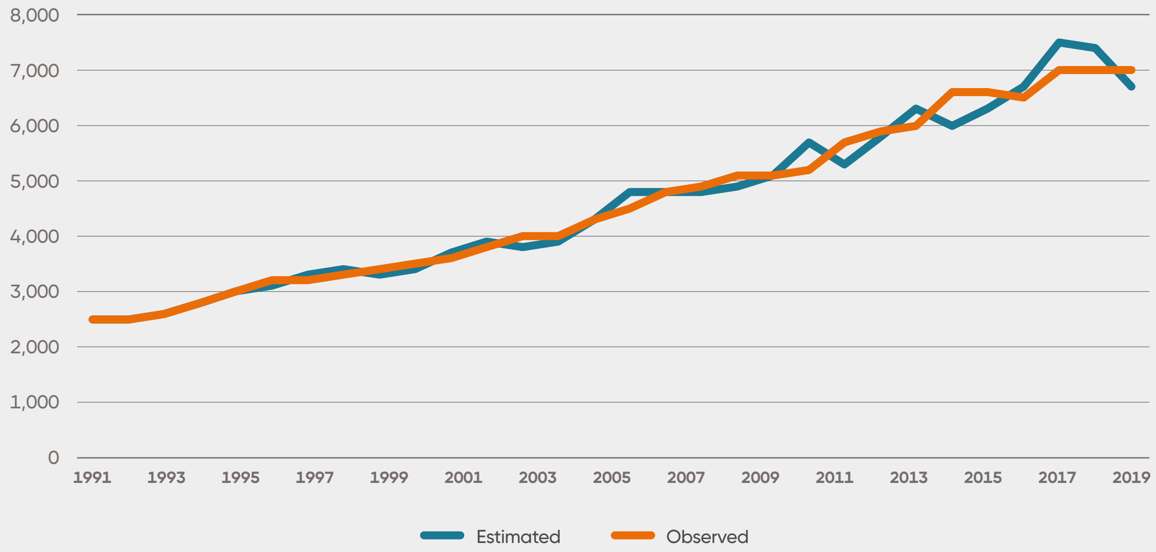
Figure C.1. Observed and estimated gross value of agricultural output from crops and livestock in millions of 2015 US dollars

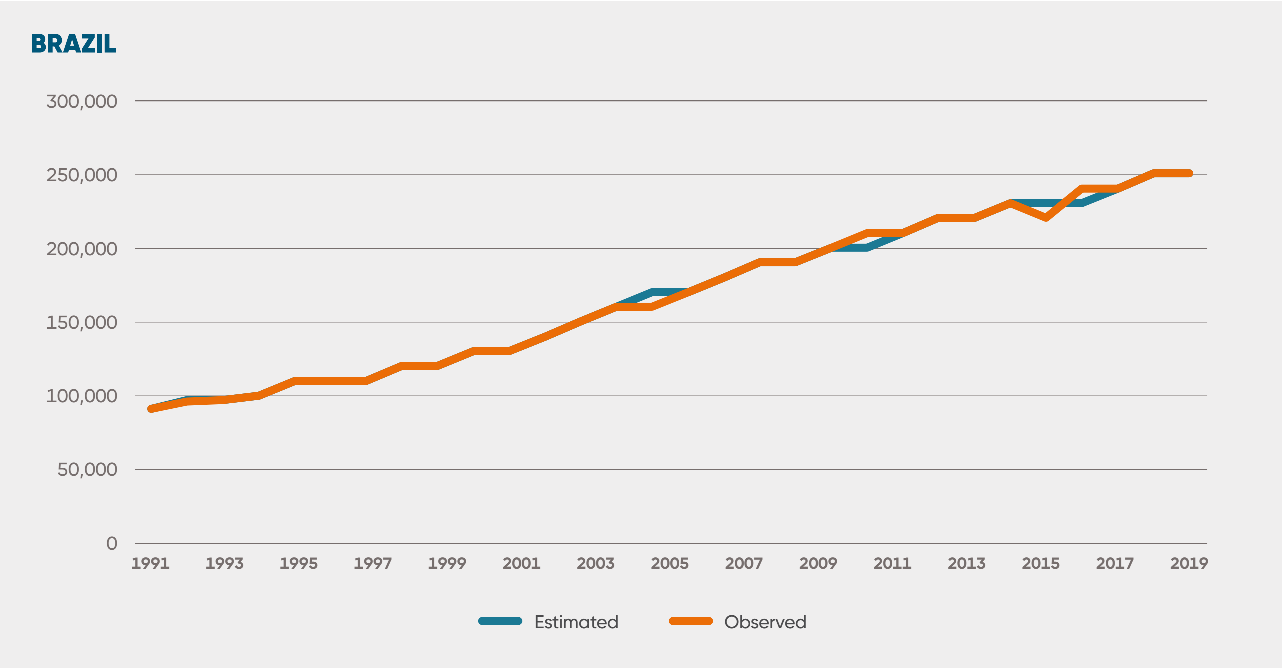


BELIZE



BOLIVIA

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200,000
150,000
100,000
50,000
0
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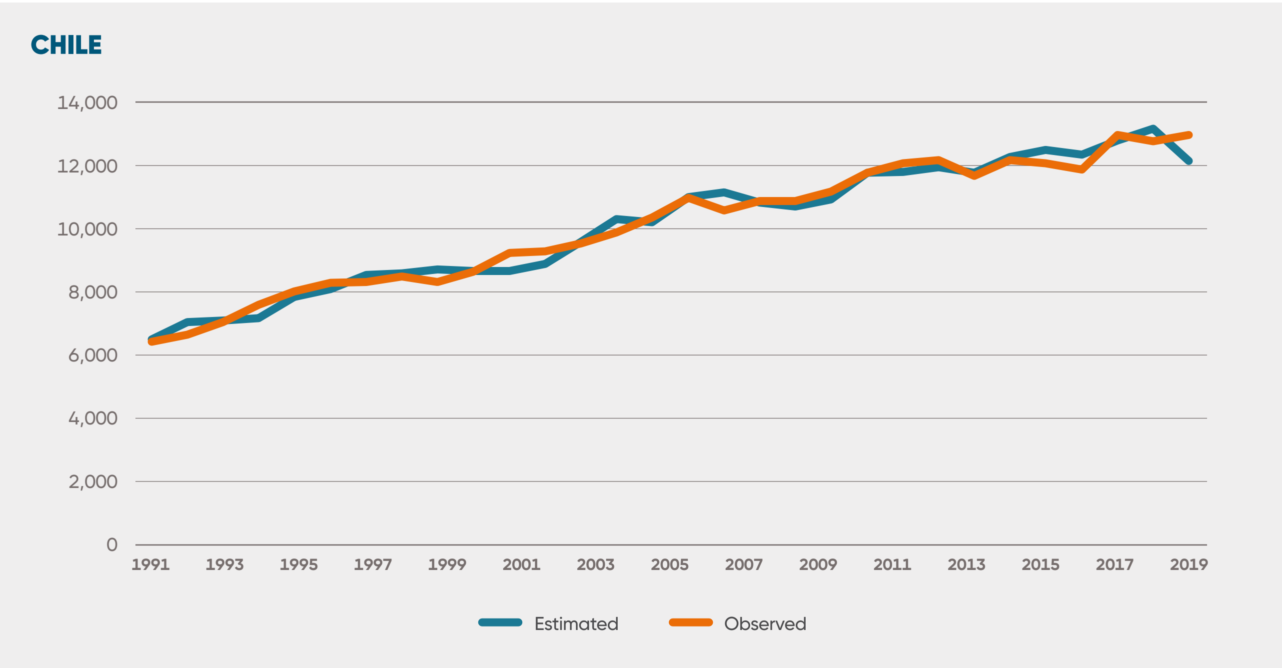
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
Estimated
Observed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10,000
8,000
6,000
4,000
2,000
0
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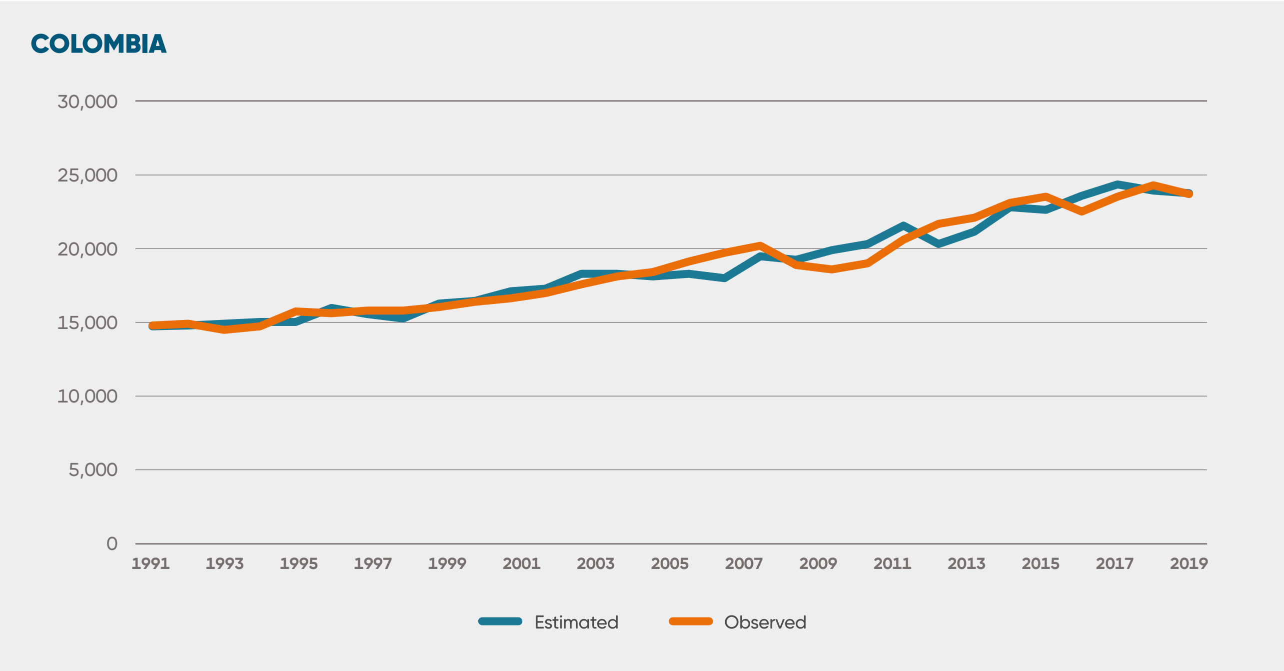
Estimated
Observed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10,000
5,000
0
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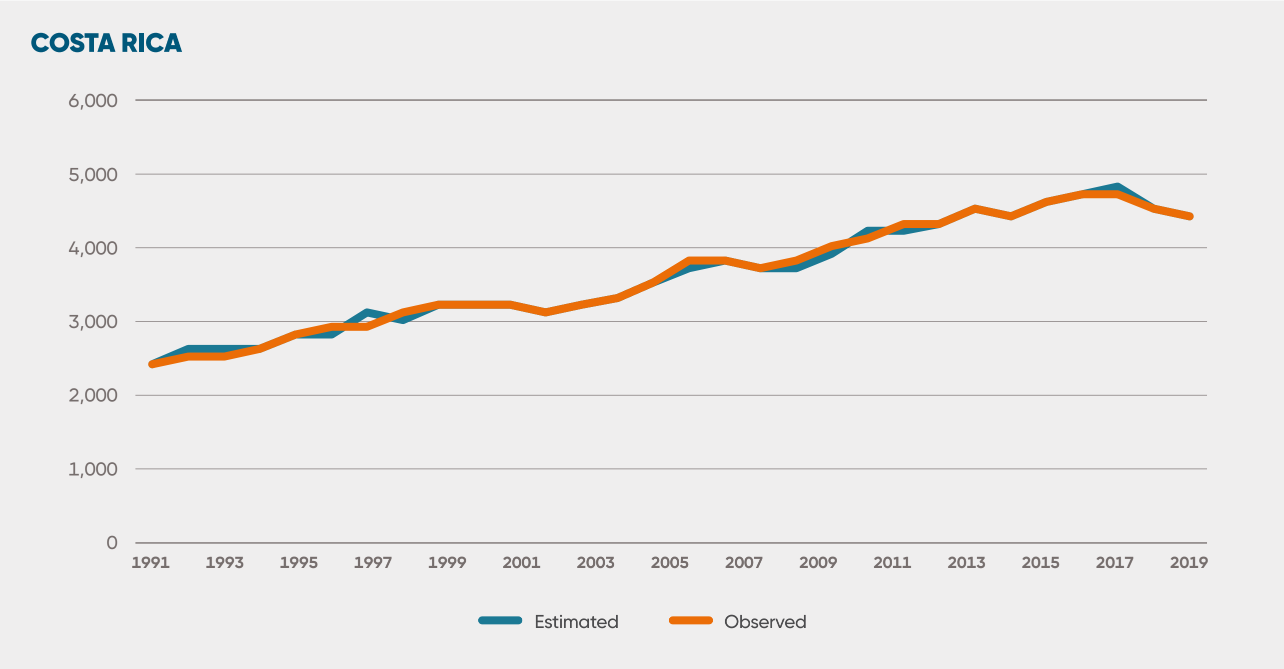
2019
Estimated
Observed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4,000
3,000
2,000
1,000
0
1991
1993
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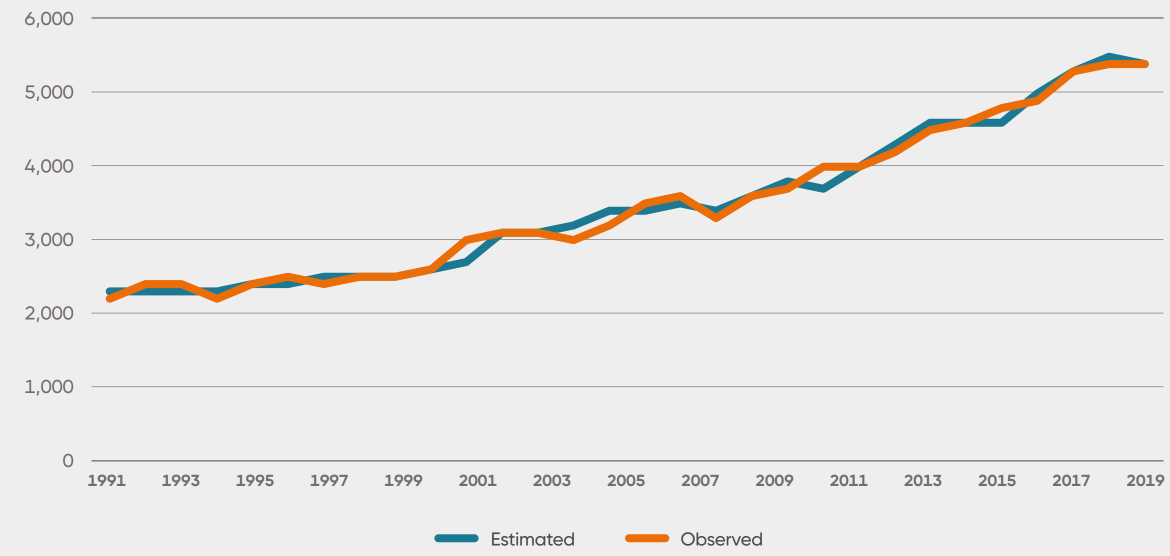
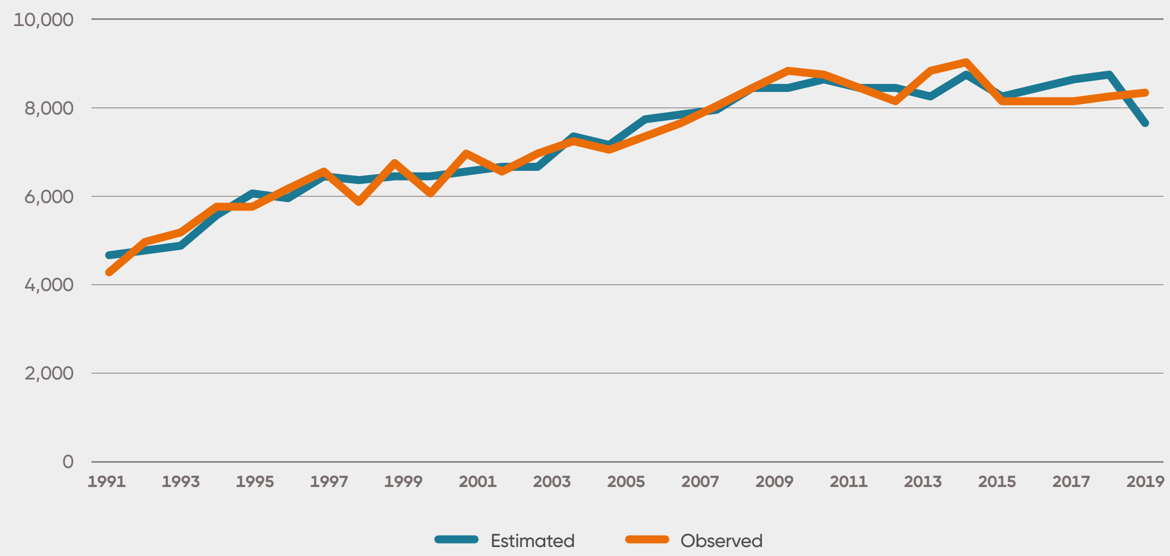
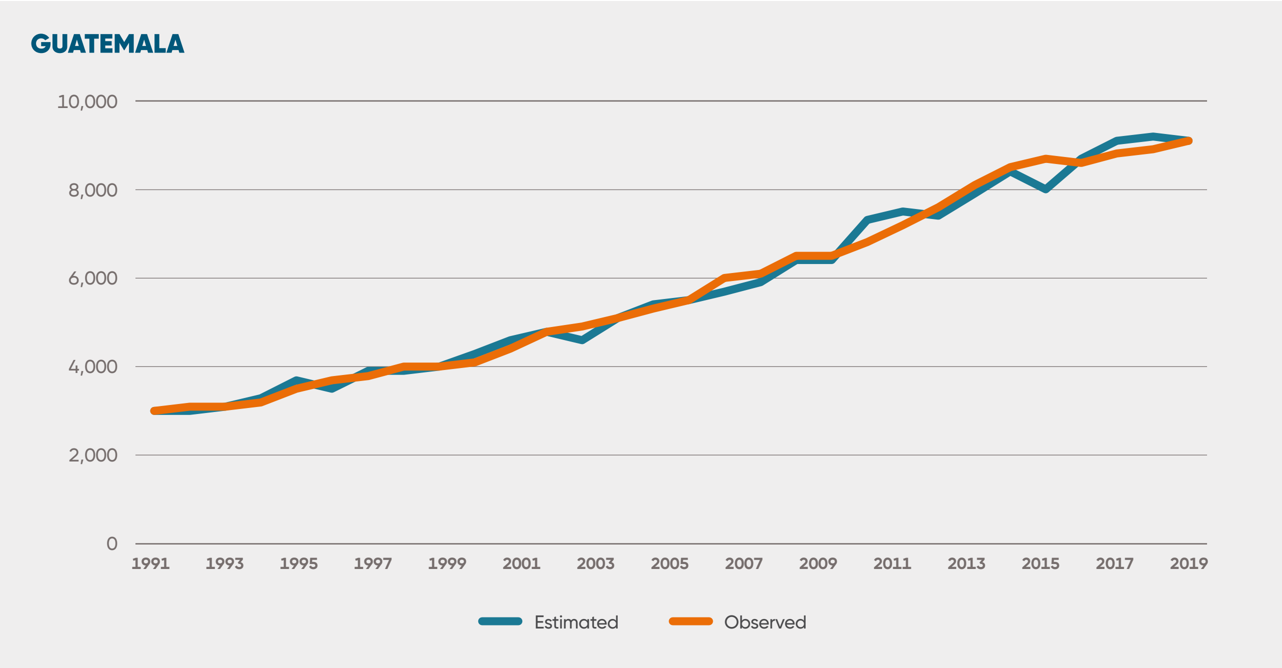
2019
Estimated
Observed

DOMINICAN REPUBLIC



ECUADOR




GUATEMALA
10,000
8,000
6,000
4,000
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1991
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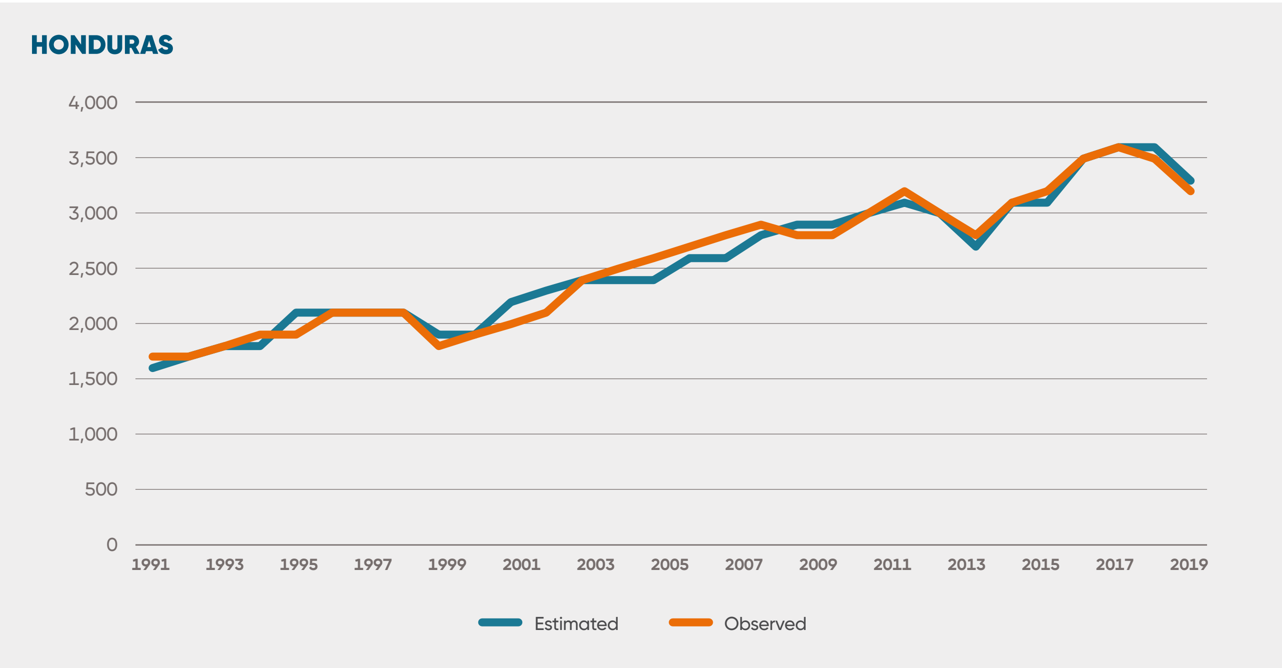
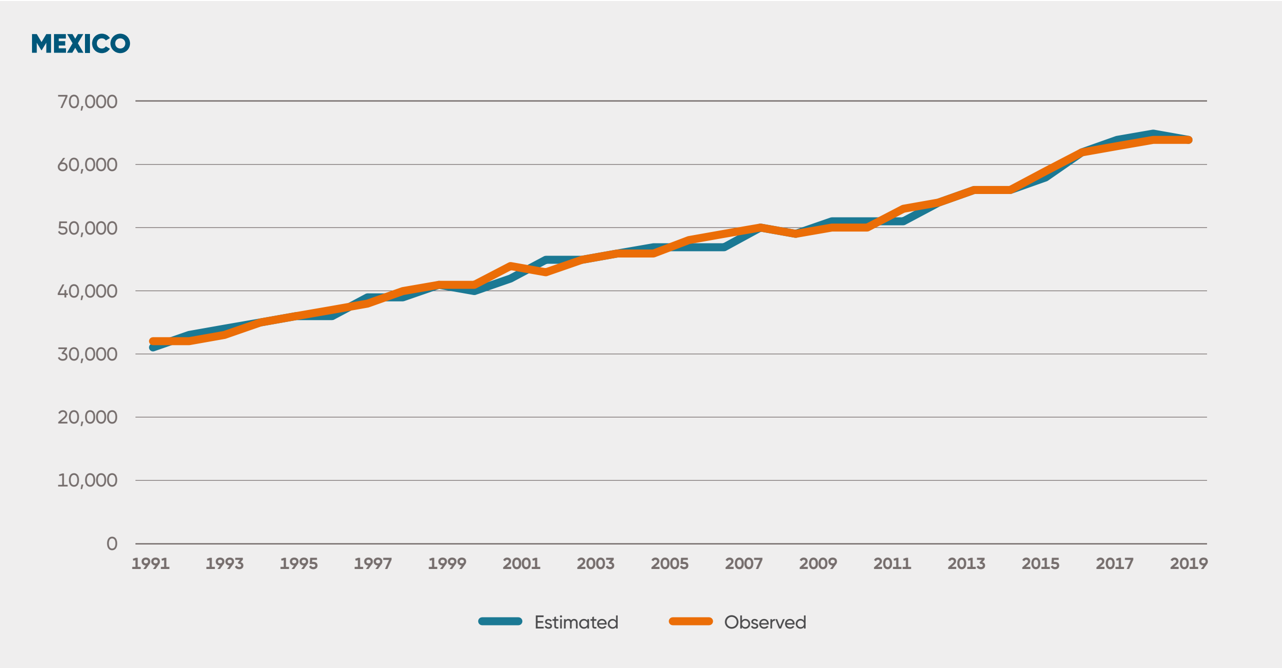
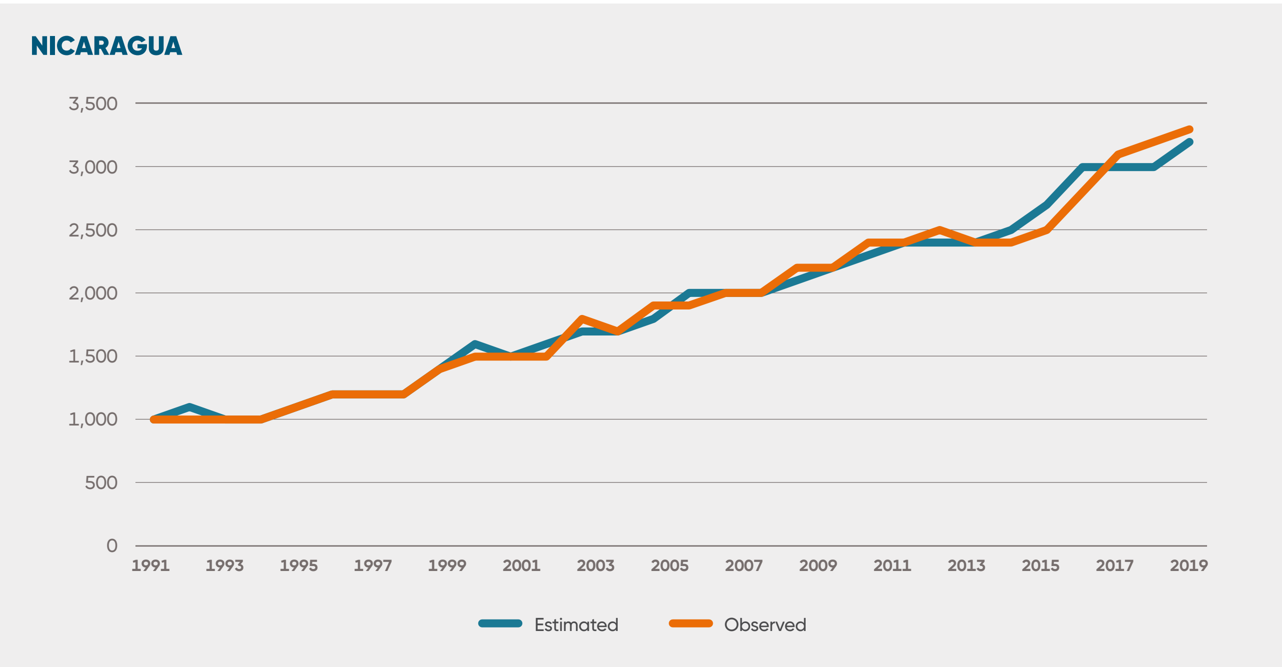
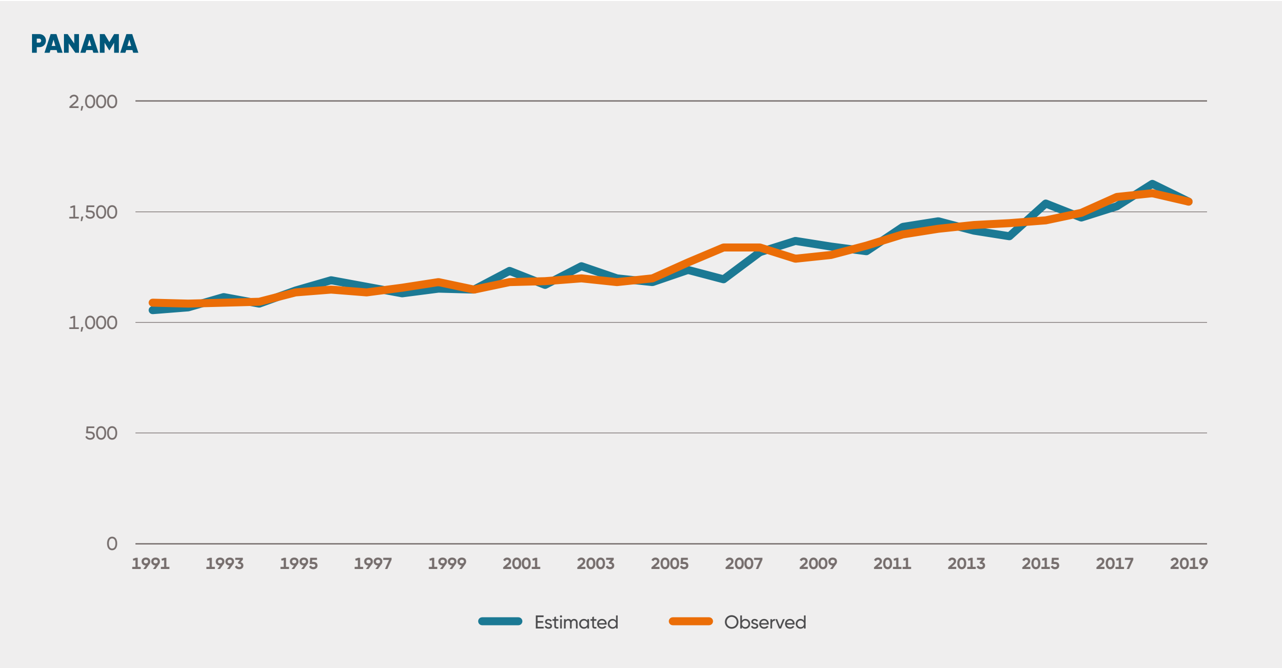
Estimated
Observed

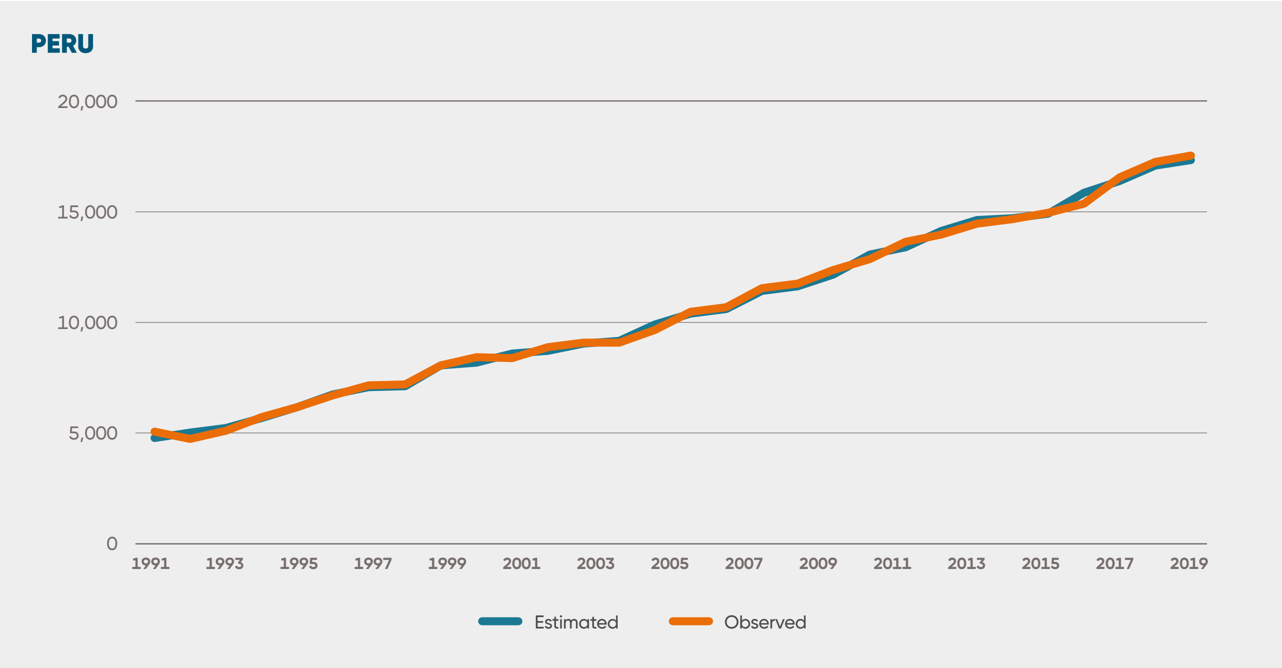

HONDURAS
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
Estimated
Observed

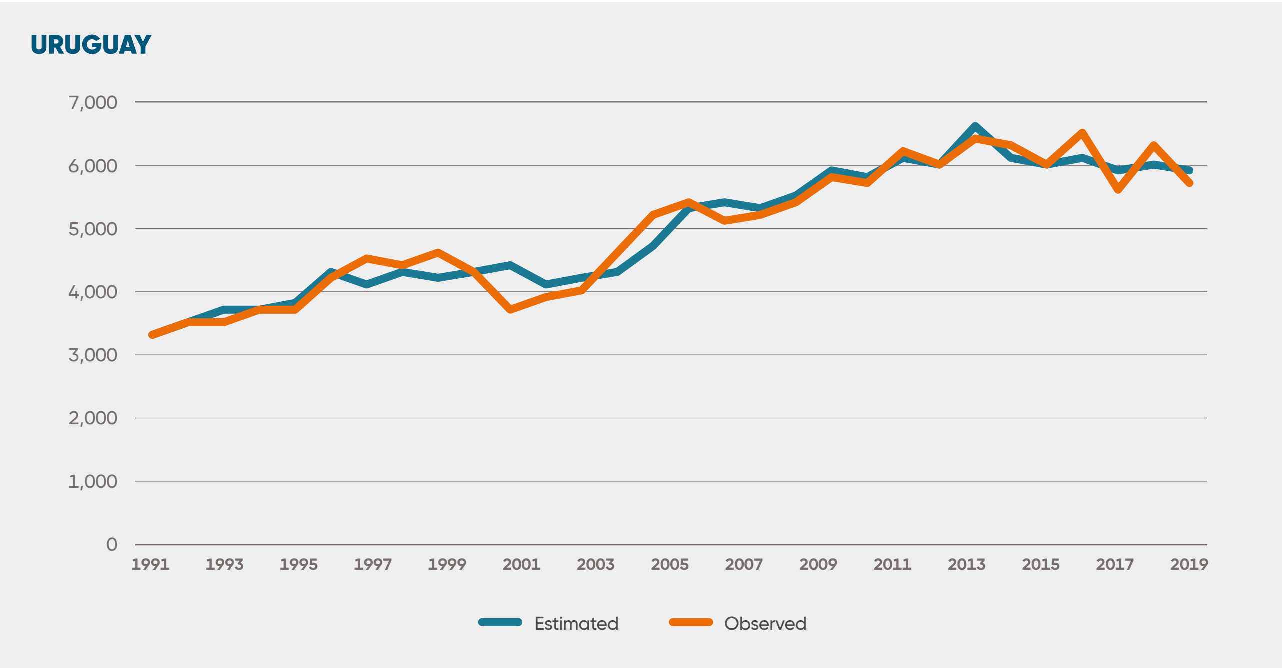

MEXICO
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
Estimated
Observed


NICARAGUA
3,500
3,000
2,500
2,000
1,500
1,000
500
0
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
Estimated
Observed


PANAMA
2,000
1,500
1,000
500
0
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
Estimated
Observed


PARAGUAY
12,000
10,000
8,000
6,000
4,000
2,000
0
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
Estimated
Observed





Source: Elaborated by authors based on USDA-ERS (2023) and ASTI (2022).

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