Food and Agriculture Organization of the United Nations

Global investments in agricultural research: Where are we and where are we going?

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Abbreviations and acronyms

AgGDP	agricultural gross domestic product
AIRCA	Association of International Research and Development Centers for Agriculture
ANBERD	OECD's Analytical Business Enterprise Research and Development database
ARI	agricultural research intensity
ASTI	Agricultural Science and Technology Indicators
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
InSTePP	International Science and Technology Practice and Policy
ISNAR	International Service for National Agricultural Research
NARS	national agricultural research systems
ODA	official development assistance
OECD	Organisation for Economic Co-operation and Development
PPP	purchasing power parity
R&D	research and development
SDGs	Sustainable Development Goals
UN	United Nations
USDA-ERS	United States Department of Agriculture's Economic Research Service
VC	venture capital
WDI	world development indicators (from the World Bank)

Executive summary

Science, technology and innovation can play a central role in transforming agrifood systems and helping countries to achieve the Sustainable Development Goals. Well-funded agricultural research and development (R&D) systems are crucial for this to happen. The fundamental importance of investing in agricultural research is evident from looking to the future and the tremendous challenges facing humankind and the world's food and agriculture systems. The advantages of investing in agricultural R&D are also clear from looking at the past, where a wide range of studies have clearly demonstrated the substantial benefits that resulted from investments in agricultural R&D. The importance of investing in R&D has also been highlighted by governments on numerous occasions in intergovernmental settings.

This report reviews the main work that has been done on measuring international investments in agricultural research. Gathering, compiling and analysing multiyear, multicountry datasets on investments in agricultural R&D are complicated tasks that require a lot of meticulous work and dedication. Only a small number of groups have worked actively in this specialized area. In some cases, they have used different procedures for gathering data on public and private sector investments in agricultural research.

For the public sector, the Agricultural Science and Technology Indicators (ASTI) initiative has carried out national surveys which have provided the main source of primary data on investments in national agricultural research systems in low- and middle-income countries over the last 20 years. For high-income countries, the main sources of data are the Organisation for Economic Co-operation and Development (OECD) databases and national reports/databases. Data on public sector agricultural R&D spending are often missing for certain countries and years. In these cases, it is common to estimate them using the national agricultural GDP (AgGDP) values and the average agricultural research intensity (i.e. agricultural research spending/AgGDP) calculated for countries in the same region.

For the private sector, there are no reliable data for most low- and middle-income countries. For high-income countries, the main data sources available are OECD databases but there are concerns about the quality and quantity of national data. Given the difficulties of getting good data, an alternative strategy of gathering data on R&D investments by major agriculture-related companies has also been employed.

Groups working in this area aim to follow the standards of the *Frascati Manual* and they tend to follow similar methodological approaches. To compare agricultural R&D investments over time and between countries, they normally use the so-called "deflate and convert" method, where R&D investments in local currency units are first deflated to a given base year (e.g. 2011) to account for inflation and then converted to international dollars using purchasing power parity (PPP) exchange rates for the base year. Gross domestic product deflators and PPP values from the World Bank's World Development Indicators database are normally used respectively for these

purposes. For improved accuracy, price indices and exchange rates should be based on the costs of agricultural R&D, but these data are seldom available.

The latest published estimates of global public and private sector investments indicate that about 60 billion 2011 PPP dollars (or international dollars) were invested in agricultural research in 2014, of which about three-quarters was from the public sector and one-quarter from the private sector. Furthermore, while different base years and datasets might have been used, five clear and common key trends emerge from the different analyses that have been carried out on investments in agricultural R&D worldwide.

First, global investments in agricultural R&D, adjusted for inflation, have increased steadily over the past 30–40 years. Research spending per capita has also increased, despite the substantial growth in the world's population over this time. While this may seem positive, it should be noted that investments in all forms of R&D have risen faster than agricultural R&D in recent years. Furthermore, the need for agricultural R&D is far greater now than it was in the past because of the tremendous challenges facing the planet, such as climate change and the broader range of research areas that need to be addressed.

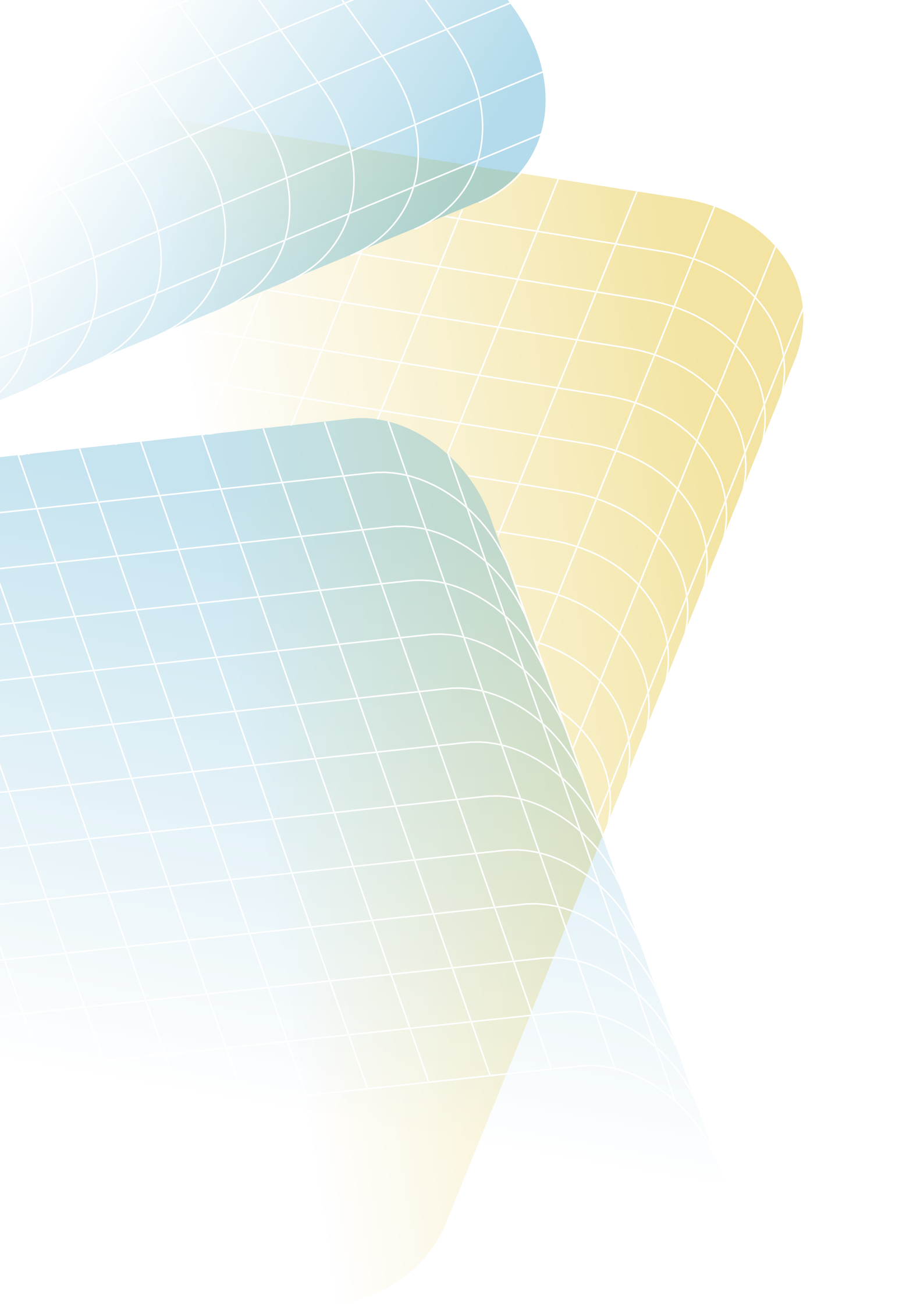
Second, the share of investments by middle-income countries is increasing and the share of investments by high-income countries is decreasing. Although spending on agricultural R&D in high-income countries has increased in recent decades, this has occurred at a much slower rate than in middle-income countries, where the major growth in spending comes from a small number of countries including India, Brazil, and especially China. Similar trends are also found when spending on global R&D, i.e. not just agriculture, is considered.

Third, most of the investments are made by a handful of high- and middle-income countries. Almost 60 percent of public sector agricultural research investments in 2016 came from just nine countries. Ranked by the size of their investments, these are China, the United States of America, India, Brazil, Japan, the Islamic Republic of Iran, France, Germany and the Republic of Korea. These same countries dominate all areas of science and technology, accounting for an estimated 78 percent of the global R&D spending in all sectors in 2018.

Fourth, investments in low-income countries continue to be extremely low and are often highly volatile. Investments in agricultural R&D have increased marginally in low-income countries in recent decades, but they remain at a meagre 2 percent of the total. In addition, funding is often unstable from year to year, making it even more difficult for national agricultural research systems in low-income countries to be efficient and carry out meaningful research that addresses the needs of their farmers. The importance of ensuring increased and stable funding for low-income countries is highlighted, as well as their strengthened engagement in partnerships in relation to agricultural research so that they can benefit from South–South, North–South and triangular cooperation.

Fifth, agricultural R&D spending by the private sector is rising faster than the public sector, so its share of the global total is increasing. While it is very encouraging that the private sector is investing more in agricultural research, it is essential that investments in public research continue to increase, as research carried out by the private sector will not replace public sector

research. Public research organizations do not need to make an economic profit and thus can work on plant and animal species and on problems facing smallholders that are not prioritized by the private sector, and on research areas involving public goods, covering topics such as environmental protection, food safety, sustainability and climate change. It is therefore essential to have a thriving well-funded public agricultural R&D system.



1. Introduction

On 25 September 2015, the 193 United Nations (UN) Member States adopted the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development to address the world's major challenges, including poverty, inequality, climate change, environmental degradation, peace and justice (UN, 2015). The SDGs are articulated in 169 targets and 231 unique indicators, and the Food and Agriculture Organization of the United Nations (FAO) is the custodian agency for 21 indicators.

Agriculture is at the heart of the 2030 Agenda for Sustainable Development and central to the commitment to "leave no one behind". The majority of the world's poor and hungry live in rural areas and depend largely on agriculture for their livelihoods. Agriculture provided employment to 866 million people in 2021 (27 percent of the global workforce) and contributed 16 and 7 percent of the gross domestic product in Africa and Asia respectively in 2020 (FAO, 2022a).

The landmark Global Sustainable Development Report (Messerli *et al.*, 2019) highlighted that there are six "entry points" that can be used to accelerate progress across all 17 SDGs, and four levers that can make it happen. One of the levers is "science and technology", and one of the entry points is "food systems and nutrition patterns", where it is highlighted that transformation of agrifood systems could lead to ending hunger and malnutrition (SDG 2) while at the same time addressing water scarcities (SDG 6), reducing climate impacts (SDG 13) and protecting life in water and on land (SDGs 14 and 15).

To underline the importance of transforming food systems, the UN Secretary-General convened the UN Food Systems Summit in September 2021 as part of the Decade of Action to achieve the SDGs. Given the importance of science, technology and innovation in achieving more efficient, inclusive, resilient and sustainable food systems, the UN established the Scientific Group for the United Nations Food Systems Summit to ensure the robustness, breadth and independence of the science underpinning the summit and its outcomes. Before the summit, the scientific group organized a two-day virtual conference entitled "Science Days for the UN Food Systems Summit 2021", facilitated and hosted by FAO, where more than 2000 participants from research, policy, civil society and industry came together to examine how to unlock the full potential of science, technology and innovation to transform food systems (Pandya-Lorch *et al.*, 2021).

So, science, technology and innovation can play a central role in developing sustainable agricultural practices and products, transforming food systems and accelerating progress towards achieving the 2030 Agenda for Sustainable Development. Investing in agricultural research and development (R&D) is crucial for this to happen.

Agricultural R&D involves a long series of steps, including the planning of research, the preparation of research projects and their implementation, the publication of results and much more. The outputs of research activities (such as a new vaccine)

then need to be made available to farmers or other relevant stakeholders so they can be adopted. It therefore takes time and does not provide rapid solutions. However, agricultural research has proven consistently and reliably that it works successfully with substantial benefits that have improved agricultural productivity and farmers' livelihoods the world over. For this reason, it has been called "slow magic" (Pardey and Beintema, 2001).

The importance of agricultural R&D for achieving SDG 2 (End hunger, achieve food security and improved nutrition and promote sustainable agriculture) was highlighted in a major study by the Center for Development Research (ZEF) and FAO aiming to identify a mix of least-cost investment options with the highest potential for reduction in hunger and malnutrition. Results from the study indicated that a bundle of promising investments that deliver long-term and short-term impacts would meet the G7 commitment of lifting 500 million people out of hunger by 2030. They considered that an incremental average annual investment of about USD 11 to 14 billion would be required for this mix of least-cost intervention options, which included agricultural R&D (ZEF and FAO, 2020; Chichaibelu *et al*., 2021).

The crucial importance of investing in agricultural research is evident from looking to the future and the tremendous challenges facing the world's food and agriculture systems. The latest "State of food insecurity and nutrition in the world" report (FAO *et al*., 2022) estimates that in 2021 there were 702–828 million people in the world who were undernourished, meaning that their habitual food consumption was insufficient to provide, on average, the amount of dietary energy they require to maintain a normal, active and healthy life.

Even when people have access to enough food for their energy needs, it may not always provide them with all the vitamins and other nutrients that they require. FAO *et al*. (2022) estimate that over 3 billion people were unable to afford a healthy diet in 2020. The report also estimates that 30 percent of women of reproductive age globally were affected by anaemia in 2019. Overweight and obesity continue to increase worldwide. For example, adult obesity nearly doubled globally from the year 2000 (343 million people) to 2016 (676 million).

At the same time, the world continues to be in a phase of exceptional population growth. The global population rose from about 2.5 billion people in 1950 to 8 billion in 2022 and it is projected to reach 8.5 billion in 2030 and 9.7 billion in 2050 (UN, 2022).

The demand for food is expected to increase substantially as the global population increases and as higher incomes drive dietary pattern changes towards more livestock products. The agriculture sectors, including forestry and fisheries, are also expected to produce more non-food products for energy and feed. At the same time, the natural resources upon which agriculture depends, such as land, water and soil, are increasingly threatened by environmental degradation and climate change.

Climate change has already begun to significantly affect agriculture. Temperatures, rain patterns, water availability, sea levels, salinization, as well as the frequency and intensity of extreme weather events, are all changing, with profound impacts on the crop, livestock, forestry and fishery sectors. Many of the countries and populations that are most affected by climate change are those that are already food insecure and malnourished.

Looking towards the future, it is imperative that food and agricultural systems are transformed so that they produce more food that is also of greater nutritional value, with less environmental damage and in the face of climate change. Agricultural research can play a fundamental role in this transformation. Since expansion of arable lands is a limited option, agricultural research should focus on sustainable intensification, continuing to expand the production frontier but in more sustainable ways in order to produce more food on less land with less water and using less fossil fuel. Relevant research areas here include enhancement of resource use efficiency in aquaculture, crops, forestry and livestock.

It is also necessary for research to go beyond production and look at the whole value chain cycle. It is estimated that up to 14 percent of food produced globally is lost between the post-harvest and retail stages and that 17 percent may be wasted at the retail, food-service and consumer stages (FAO, 2022b). Relevant research areas here include strategies to increase the shelf-life of fruit and vegetables and involve the social sciences to understand consumers' behaviour so they will reduce food waste. To improve nutrition, relevant research areas include the development of biofortified crop varieties or the study of national policies that have been adopted to combat rising obesity rates. For adaptation to climate change, relevant research areas include the development of diagnostic tools and vaccines for emerging diseases, or the study of crop varieties that are tolerant to extreme weather events, such as flooding or extreme drought. For the mitigation of climate change, relevant research areas include the study of the microbiome to reduce methane emissions from ruminants or the study of carbon sequestration by the soil. It is important to apply more transdisciplinary approaches so that agricultural research goes beyond production and productivity and encompasses broader social and environmental food systems issues (Global Alliance for the Future of Food, 2021).

The world's family farmers, who manage over 550 million farms, covering 70–80 percent of farmland worldwide and producing about 80 percent of the world's food (Lowder, Sánchez and Bertini, 2019), will be central for the transformation of food and agricultural systems (Ruane, ed., 2019). Farmers' participation in formal R&D programmes can help ensure that the research is relevant to their needs and their specific circumstances.

Therefore, looking to the tremendous challenges facing humankind in the future, it is obvious that investing in agricultural research is imperative. However, the benefits of investing in agricultural R&D are also clear from looking at the past. A wide range of studies have been carried out to assess the economic returns deriving from investments in agricultural R&D, typically reporting the net present value (NPV), the benefit–cost ratio (BCR) or, most commonly, the internal rate of return (IRR).[1]

Pardey *et al*. (2018) reviewed the economic returns to public and private R&D in food and agriculture using a database including 3426 rate of return estimates from 492 separate studies published between 1958 and 2015. They found that the median IRR was 37.5 per cent per year (based on 2627 estimates) and the median BCR was 12 (based on 799 estimates). While there has been discussion about the assumptions and interpretations made when estimating

1 The NPV is the present value of the economic benefits of the R&D minus the present value of the R&D costs; BCR is the ratio of the present value of benefits to the present values of costs; and IRR is the discount rate at which the NPV is zero.

economic returns to agricultural R&D (see e.g. Rao, Hurley and Pardey, 2019; Alston and Pardey, 2022), there is nevertheless strong and clear evidence that the economic returns to food and agricultural R&D have been high (Pardey *et al*., 2018).

While the academic literature contains substantial numbers of studies that have examined the economic benefits of agricultural research, fewer studies have been carried out to investigate the benefits of agricultural research for other areas where economic returns are not the main goal, such as the environment, climate change, natural resources management, human health or nutrition, food security or poverty, gender issues, or government policy. Evaluating the benefits of agricultural research in such areas can provide challenges with respect to methodologies and data collection. Nevertheless, studies indicate that, as for economic returns, the benefits of agricultural R&D for such non-economic goals can be substantial. For example, from a series of seven case studies, Adato and Meinzen-Dick (eds., 2007) indicated that agricultural research can have a beneficial impact on poverty through direct effects on farm households that adopt the resulting technologies and through indirect effects on the wider population. SPIA (2019) summarized the findings from 25 impact assessments commissioned by the CGIAR Standing Panel on Impact Assessment (SPIA), examining the impacts of a wide range of innovations from three main areas of CGIAR research – crop improvement, production systems management and policy. The studies documented that positive impacts can be realized for poverty, food security, nutrition and environmental outcomes. They also showed the complexity of measuring these kinds of impacts and achieving impacts in real-world settings.

Recognition of the importance of agricultural research investments in international settings

The importance of investing in R&D has also been highlighted by governments on numerous occasions in intergovernmental settings. For example, in 2004, the United Nations Economic and Social Council (ECOSOC) adopted a resolution on Science and Technology for Development recommending that governments increase their R&D expenditure in science and technology to at least 1 percent of the national gross domestic product (ECOSOC, 2004).

In 2014, in Malabo, Equatorial Guinea, the African Union Heads of State and Government adopted the Declaration on Accelerated Agricultural Growth and Transformation (i.e. the Malabo Declaration). The Declaration has seven commitments, one of which is "Ending hunger in Africa by 2025". They also committed to conducting a biennial review to track, monitor and report on progress in achieving the Declaration's provisions. For this purpose, in 2018, the African Union launched the Africa Agriculture Transformation Scorecard (African Union, 2018). The Scorecard contains 43 indicators, expanded to 47 in the 2020 review, including a target for each one to indicate whether the countries are on track. One of the 43 indicators is "Total agricultural research spending as a share of AgGDP" and the target is 1 percent.

The need to increase R&D investments is also embedded within the SDGs adopted by 193 UN Member States in 2015. Target 9.5 of SDG 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation) is to "Enhance scientific research, upgrade

the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending." One of the two indicators for this target is "Research and development expenditure as a proportion of GDP". Furthermore, specifically relating to agricultural research, target 2.a of SDG 2 is to "Increase investment, including through enhanced international cooperation, in rural infrastructure, *agricultural research* and extension services, technology development and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries" (italics added).

So, the importance of investing in agricultural R&D is evident from looking both to the future and the past and its importance has been recognized by governments worldwide. In this report we aim to provide an updated overview of the global situation and trends regarding public and private sector investments in agricultural R&D worldwide. In Section 2, we describe the major initiatives that have been undertaken to measure global investments in agricultural research, including the data sources and methodologies that have been used and some of the main results that have been found. In Section 3 we discuss the results and then present some key conclusions and recommendations in Section 4.

The report befitted from the initial exchanges in 2020 with Nienke Beintema, Paul Heisey and Gert-Jan Stads.

2. The main work that has been done on measuring international investments in agricultural research

Gathering, compiling and analysing multiyear, multicountry datasets on investments in agricultural R&D are complicated tasks that require a lot of meticulous work and dedication. Only a small number of people/groups actively work in this specialized area. Some of them use primary data (i.e. collected by the researchers during their work) while others use secondary data (previously existing data), compiled by bodies such as the Organisation for Economic Co-operation and Development (OECD). They all aim to follow the principles and definitions laid out in the authoritative *Frascati Manual*, whose guidelines are considered the standard worldwide for collecting R&D data (OECD, 2015). Different procedures are followed for gathering data on public or private sector investments in agricultural research.

For the public sector, the Agricultural Science and Technology Indicators (ASTI) initiative has carried out national surveys which have been the key source of primary data on investments in national agricultural research systems of low- and middle-income countries over the last 20 years. For high-income countries, the main sources of data are OECD databases and national reports/ databases.

Data on public sector agricultural R&D spending are often missing for specific countries in specific years. In these cases, it is common to estimate them using the average regional agricultural research intensity (ARI) and national agricultural gross domestic product (AgGDP). The background to this "ARI-AgGDP approach" is that when analyses are carried out on total national R&D investments, in addition to absolute numbers, it is standard practice to also express the investments as a proportion of the GDP, termed the R&D intensity or research intensity (e.g. Soete *et al*., 2015). This is also done for the specific area of agriculture, where investments in agricultural R&D are expressed as a percentage of the GDP coming from the agricultural sector (i.e. the AgGDP), termed ARI, that is:

ARI = 100 x agricultural research expenditures/AgGDP

When data on agricultural research expenditures are missing for a country, this formula can be used to provide a rough estimate of its research expenditures. This is done by calculating the ARI for countries in the same region to get a regional average and then multiplying it by the country estimate of the AgGDP taken from the World Bank's World Development Indicators (WDI) database.[2] This method assumes that the ARI of the country is the same as the regional average.

2 https://databank.worldbank.org/source/world-development-indicators

For the private sector, there are no reliable data for most low- and middle-income countries. The ASTI national surveys also aim to collect data on private sector investments, but ASTI (2016) notes the difficulties of getting complete and accurate figures for the private sector as many private companies are reluctant to share such information due to confidentiality concerns. In addition, private research activities in low- and middle-income countries tend to be small-scale and ad hoc, making it difficult to capture in national surveys. For high-income countries, data collection is challenging and there are concerns about the quality and quantity of national data. The main data sources available are OECD databases. Given the difficulties of getting good data, an alternative strategy of gathering data on agricultural R&D investments by leading companies has also been employed.

Having gathered the public and/or private sector data, the method of choice to compare agricultural R&D investments over time and between countries is the so-called "deflate and convert" method. Most international comparisons of agricultural research investments over the past 30 years have used it (Pardey *et al*., 2016a; Heisey and Fuglie, 2018a). The method entails that, first, to account for inflation (and get the "real" or constant value), spending in local currency units (i.e. "nominal" values) is deflated to a given base year (e.g. 2011), thus making it possible to compare spending within a country over different years. This is done using GDP deflators for the country from the World Bank's WDI database.

Second, to allow for comparisons across countries, the R&D spending estimates, now in constant local currency units, are converted to base year (e.g. 2011) international dollars using purchasing power parity (PPP) exchange rates for 2011, normally taken from the World Bank's WDI database. The PPP exchange rates express the relative purchasing power of different currencies using the local prices of a common basket of local goods and services, gathered from surveys on household consumption, government consumption, machinery and equipment, and construction and civil engineering. Whereas market exchange rates are valid if considering internationally traded goods and services, PPP exchange rates are preferred because they reflect the relative purchasing power of different currencies in their national markets (World Bank, 2020).

Having looked at these overarching issues, we will now briefly look at the work done by the small number of groups working in this area. The key characteristics of data used in main recent studies by these groups are presented in Table 1.

2.1 ASTI work on public sector agricultural R&D spending

The ASTI initiative has worked with a large network of country-level collaborators who implement national surveys to collect primary data from government, higher education, non-profit and private for-profit agencies involved in agricultural R&D in low- and middle-income countries worldwide.[3] The surveys also gather detailed information on the number of researchers working on specific commodities and in specific areas of research.[4] Details of the

3 The income grouping of countries follows the World Bank classification: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups. The groupings are reviewed by the World Bank each year and can change over time.

4 Detailed findings for each country surveyed are available at www.asti.cgiar.org/countries

Table 1. Key characteristics of main recent studies aiming to estimate global investments in agricultural (and food) R&D

Author(s) of the study	Main novelty of their work	Data source: public sector low- and middle-income countries	Data source: public sector high-income countries	Data source: private sector	PPP base year
Beintema, Nin Pratt and Stads (2020)	Release of updated results (until 2016) from ASTI national surveys of public sector investments in low- and middle-income countries	ASTI national surveys	OECD database, until 2016	Fuglie (2016), until 2014	2011
Heisey and Fuglie (2018a, 2018b)	Release of results from a time series of public sector spending in 31 high-income countries from 1960 (for most countries) to 2013	ASTI data for 1990 and 2011	OECD and national sources,	Fuglie (2016), data for 1990 and 2011	2011
Fuglie (2016)	Release of results from an updated (until 2014) and extended database of R&D spending by leading companies in seven areas of agricultural inputs	Not used	Not used	Own database on agricultural R&D; Estimates of food sector R&D from the OECD Analytical Business Enterprise Research and Development (ANBERD) database (http://oe.cd/anberd), until 2012	2005
Pardey *et al*. (2016b)	Release of results from an updated database of public and private sector R&D spending in agriculture and in food manufacturing/processing from 1960 to 2011	Mostly ASTI in later years	OECD databases and national data, until 2011	Own database of private firms for the United States of America; Estimates from the OECD ANBERD database for other high-income countries; Estimates from national data for a small number of middle-income countries; Estimates from an econometric model for most low- and middle-income countries; Until 2011	2009

definitions, methodologies and data collection standards used are described in detail on its website[5] and the practitioner's guide (ASTI, 2016) and further information is provided in the Annex.

At periodic intervals, ASTI compiles the latest results from its national surveys on public spending in low- and middle-income countries and, together with data from other sources, publishes a global overview. The latest one covers 128 low- and middle-income countries and 51 high-income countries, and includes data up to 2016, expressing investments in constant 2011 PPP dollars (Beintema, Nin Pratt and Stads, 2020).[6] For the 128 low- and middle-income countries, data for 87 countries came from ASTI national surveys or surveys carried out by ASTI together with other national/regional partners; for nine countries they were from other sources (e.g. EUROSTAT); and for 32 countries the data were not available and so they were estimated using the ARI-AgGDP approach. For the 51 high-income countries, the data sources for 28 countries were the OECD Main Science and Technology Indicators database,[7] nine were from other sources and 14 were estimated using the ARI-AgGDP approach.

For public sector investments, the global update shows that spending on agricultural research continues to grow globally. Table 2 shows that in the years 1981, 2000 and 2016, investments rose from 21.1 to 30.9 and 46.8 billion 2011 PPP dollars.[8]

The increase in investments by middle-income countries is substantial. From 2000 to 2016, the share of total agricultural research spending by middle-income countries rose from 40 to 58 percent. Most of this was due to China, India and Brazil, where spending rose from 1.0, 1.6 and 1.8 billion 2011 PPP dollars in 2000 to 7.7, 4.0 and 2.7 billion 2011 PPP dollars in 2016 respectively.

From 2000 to 2016, the share of the total agricultural research spending coming from high-income countries declined correspondingly, from 58 to 40 percent. High-income countries spent 18.0 billion 2011 PPP dollars in 2000 which rose to 18.6 billion 2011 PPP dollars by 2016. However, in the same time period, spending in middle-income countries rose much more, from 12.4 to 27.3 billion 2011 PPP dollars.

Across the world, there are huge inequalities in agricultural research spending. Some countries invest substantial amounts of money. Countries with the highest public sector investments in 2016 were China (7.7 billion 2011 PPP dollars), the United States of America (4.5), India (4.0), Brazil (2.7), Japan (2.6), the Islamic Republic of Iran (1.9), France (1.5), Germany (1.3) and the Republic of Korea (1.1) respectively. The top three spenders (namely China, the United States of America and India) were responsible for 35 percent of the global public sector investments in 2016. The top five and the top nine spenders were responsible for 46 and 59 percent respectively of the global public sector investments in 2016. At the other extreme, there were 52 countries which each spent less than 10 million 2011 PPP dollars in 2016. The share of public sector agricultural research spending by low-income countries was a dismal 2 percent in 2016, the same as in 2000 and 1981.

5 www.asti.cgiar.org/methodology

6 Country-level data sources are available at www.asti.cgiar.org/pdf/Country-Data-Sources-and-Estimation2020.pdf

7 www.oecd.org/sti/msti.htm

8 As described earlier, when spending is expressed in this format it means the expenditures in different years for a given country were first adjusted for inflation and expressed relative to a base year (2011 in this case) and then converted to international dollars (or PPP dollars) using PPP values which express the relative purchasing power of a country's currency, using a common basket of local goods and services.

Table 2. Public sector spending on agricultural R&D (in billion 2011 PPP dollars and percentages of the total for specific years)

	Billion 2011 PPP dollars			Percentages		
	1981	2000	2016	1981	2000	2016
High-income countries	12.8	18.0	18.6	61	58	40
Middle-income countries	7.9	12.4	27.3	37	40	58
Low-income countries	0.4	0.5	0.8	2	2	2
Total	21.1	30.9	46.8	100	100	100

Source: Adapted from (N. Beintema, Personal communication, 2020) and N., Beintema, N., Nin Pratt, A. & Stads, G.J. 2020. *ASTI global update 2020*. Washington D.C., International Food Policy Research Institute. www.asti.cgiar.org/publications/global-update-2020

As noted earlier, in addition to absolute numbers, it is standard practice to express investments in agricultural research in relation to the AgGDP (i.e. the ARI). Beintema, Nin Pratt and Stads (2020) estimate that in 2016, the ARI for all countries worldwide was 0.72 percent (meaning that for every 100 dollars of agricultural GDP, 72 cents were spent on agricultural R&D). For low-income countries it was 0.34 percent. For middle-income countries excluding Brazil, China and India, it was 0.24. For Brazil, China and India it was 1.95, 0.45 and 0.3 percent, respectively. For high-income countries, it was about 2.8 percent. Looking back over the past 35 years, the average ARI for low- and middle-income countries as a group, and for individual regions, remained fairly constant over time, indicating that the growth in agricultural research spending largely followed the pattern of AgGDP growth. In contrast, the average ARI in high-income countries increased from 1981 onwards, before decreasing in recent years.

To compare public and private sector expenditures, Beintema, Nin Pratt and Stads (2020) also included data on the private sector in their global update. These were from Fuglie (2016), discussed later in Section 2.2, who estimated global private sector investments by leading companies in seven agricultural input sectors up to 2014. For multinational companies, R&D investments were assigned to the country where the corporate headquarters is allocated. Figures from Fuglie (2016) were converted from 2005 PPP dollars to 2011 PPP dollars so they could be compared directly to the public sector estimates.

Table 3 shows that, like the public sector, investments from the private sector are also growing, but at a slightly faster rate. Private sector spending rose from 7.6 billion 2011 PPP dollars in 1990 to 8.9 and 15.5 billion 2011 PPP dollars in 2000 and 2014 respectively. Most of the expenditures were in high-income countries. Private sector spending in high-income countries rose from 7.3 billion 2011 PPP dollars in 1990 to 8.4 and 13.5 billion 2011 PPP dollars in 2000 and 2014 respectively. In low- and middle-income countries, it rose from 0.3 billion 2011 PPP dollars in 1990 to 0.5 and 2.0 billion 2011 PPP dollars in 2000 and 2014, respectively. The total global expenditure on agricultural research worldwide was 59.3 billion 2011 PPP dollars

Table 3. Public and private sector spending on agricultural R&D (in billion 2011 PPP dollars and percentages of the total for specific years)

	Billion 2011 PPP dollars			Percentages		
	1990	2000	2014	1990	2000	2014
Public						
High-income countries	15.4	18.0	18.6	46	45	31
Low- and middle-income countries	10.5	12.9	25.2	31	33	42
Total	25.9	30.9	43.8	77	78	74
Private						
High-income countries	7.3	8.4	13.5	22	21	23
Low- and middle-income countries	0.3	0.5	2.0	1	1	3
Total	7.6	8.9	15.5	23	22	26
All investments	33.5	39.7	59.3	100	100	100

Source: Adapted from (G.J. Stads, personal communication, 2020) and N., Beintema, N., Nin Pratt, A. & Stads, G.J. 2020. *ASTI global update 2020*. Washington D.C., International Food Policy Research Institute. www.asti.cgiar.org/publications/global-update-2020
Note: Private sector spending does not include the food manufacturing industry

in 2014, of which 15.5 billion 2011 PPP dollars (26 percent) was from the private sector. For 2000, this share was 22 percent.

As mentioned earlier, the ASTI surveys also gather detailed information on the number of researchers, measured in full-time equivalents,[9] working on specific commodities and in specific areas of research. Beintema (2020a) presents the results from 83 low- and middle-income countries in the mid-2010s for which detailed data were available. She shows that, on average, 50 percent of researchers carried out research on crops; 16 percent worked on livestock issues (including veterinary medicine); 18 percent worked on forestry, fisheries and natural resources; and 17 percent worked on areas such as socioeconomics, agricultural engineering and on-farm post-harvest activities. These proportions remained quite constant when the data for the 83 countries were analysed by world region or by income group (low versus medium). Beintema (2020a) reports, nevertheless, that there were individual country variations. For example, researchers in Botswana worked more on issues related to livestock than crops, those in Indonesia gave a relatively high focus to forestry, while those in Mauritania gave a lot of attention to fisheries.

9 This refers to the proportion of time spent on R&D during the year. For example, if a researcher normally spends 70 percent of the working hours on R&D and 30 percent on other activities, such as teaching and administration, this represents 0.7 full-time equivalents.

Looking at crop research in detail, Beintema (2020a) found that researchers in the 83 countries worked mostly on cereals (28 percent), horticultural crops (26), oil-bearing crops (11), pulses (8), roots and tubers (7) and others (19). These proportions varied by world region. For example, in sub-Saharan Africa, cereals, roots and tubers represented 57 percent of the researched crops, while horticultural crops represented 16 percent. In contrast, in West Asia and North Africa, cereals, roots and tubers represented 40 percent of the researched crops, while horticultural crops represented 36 percent.

The previous ASTI global update was published by Beintema *et al.* (2012)[10] with colleagues from the United States Department of Agriculture's Economic Research Service (USDA-ERS). The update looked at the global situation up to 2008, expressed the spending in 2005 PPP dollars and covered 179 countries, of which 31 were classified as low-income countries, 102 as middle-income countries and 46 as high-income countries. For the 133 low- and middle-income countries, the analysis used ASTI national survey data for 67 countries (50 percent of the countries), data from other sources for 8 countries (6 percent) while for 58 countries (44 percent), data were not available, so they were estimated using the ARI-AgGDP approach. For the 46 high-income countries, estimates for 28 countries were from the OECD database, 3 were from other sources and 15 were from the ARI-AgGDP approach.

10 Data used in the analysis for public agricultural research investments, ARIs, AgGDP and other variables, for the different regions, income groups and some specific countries are available at www.asti.cgiar.org/pdf/GlobalAssessmentDataTables.pdf. Country-level data sources and estimation procedures, organized by region and income group (low-/middle- vs high-income) are available at www.asti.cgiar.org/pdf/CountrySourcesEstimations.pdf.

2.2 USDA-ERS work on global private sector agricultural R&D spending

As described in more detail in the Annex, economists at the USDA-ERS established a database of R&D investments by leading firms, described by Fuglie *et al*. (2011, 2012) and later expanded and updated it to include 324 leading companies worldwide conducting research in seven sectors of agricultural inputs (Fuglie, 2016). The seven agricultural input sectors included three for crops (i.e. seeds and biotechnology, pesticides and fertilizers), three for animals (genetics, health and nutrition) and the farm machinery sector. The animal sector included aquaculture. The database included 182 companies that were operating in 2014, and 142 that had operated at some time during the 1990–2013 period but were no longer operational, e.g. because of a merger. A total of 226 leading firms were doing research in the crops sector, 62 in the animal sector and 40 in the farm machinery sector.

For the seven agricultural input sectors, the study showed that between 1990 and 2014, private agricultural R&D spending worldwide doubled, rising from 6.4 billion to 12.9 billion constant 2005 PPP dollars (Table 4). His analysis showed that most companies focused their agricultural R&D on either crops, animals or farm machinery, although a few had significant R&D in both crops and animals. The R&D by farm machinery companies is also mostly focused on crop operations. He also showed that a few companies dominate. Five companies (four in the crop sector and one farm machinery company) each had agricultural R&D budgets greater than USD 1 billion (nominal) in 2014 – representing nearly 40 percent of the total global agricultural R&D by the private sector. Eight companies had agricultural R&D budgets greater than USD 0.5 billion, and they were responsible for over one-half of all

Table 4. Private sector spending on R&D in seven agricultural input areas and in food manufacturing (in billion 2005 PPP dollars) over different years

	1990	1995	2000	2005	2012	2014
Crops (seeds and biotechnology, pesticides and fertilizers)	4.1	4.6	4.6	4.7	7.0	7.6
Animal (genetics, health and nutrition)	1.2	1.3	1.3	1.5	2.1	2.2
Farm machinery	1.1	1.1	1.3	1.4	3.0	3.1
Total agriculture	6.4	7.0	7.3	7.6	12.0	12.9
Food manufacturing	6.4	7.6	7.0	9.7	18.7	–
Total food and agriculture	12.8	14.6	14.3	17.3	30.8	–

Source: Adapted from Fuglie, K. 2016. The growing role of the private sector in agricultural research and development world-wide. *Global Food Security*, 10, 29–38. Table 4. https://doi.org/10.1016/j.gfs.2016.07.005

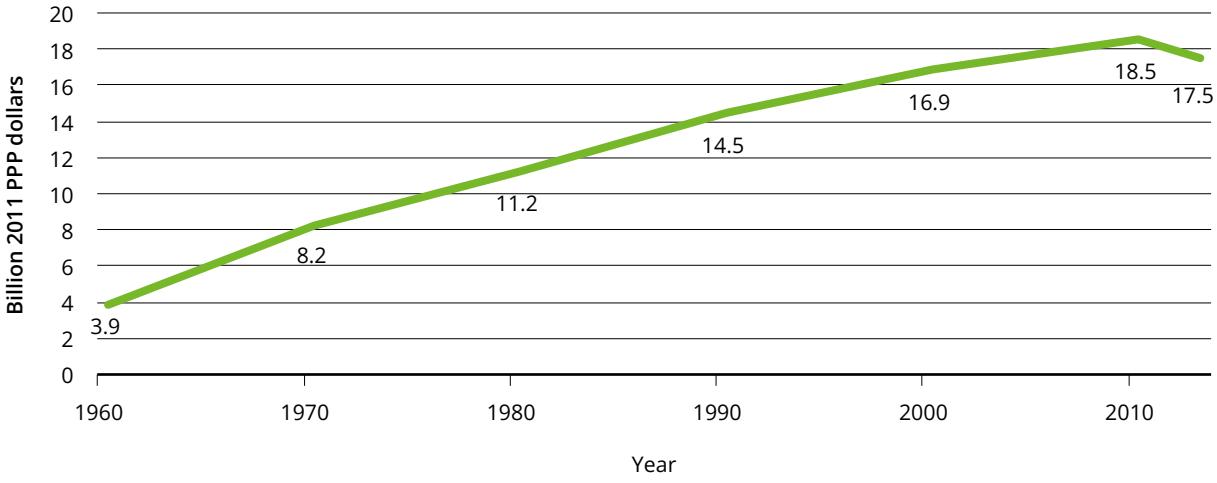
agricultural R&D. Twenty-three companies spent at least USD 100 million each on agricultural R&D in 2014, accounting for over 70 percent of the total global agricultural R&D by the private sector.

Firms do not report R&D spending by commodity, so it is not straightforward to estimate R&D allocations to different commodities. However, estimates of the size of global agricultural input markets are available, and total private crop and animal R&D can be allocated in proportion to the share that different commodities have in these markets. Using this approach, Fuglie (2016) estimated that the largest R&D allocations were for corn, soybeans, vegetables and fruit, and that relatively few R&D investments were directed to root and tuber crops, bananas and plantains, many species of vegetables and fruit crops, smallholder tree crops, ruminants, or aquaculture.

For comparison purposes, Fuglie (2016) also included estimates of R&D spending in the food processing or food manufacturing industry. For this, he relied primarily on country-level estimates from the OECD's ANBERD database, covering OECD countries and a selection of non-OECD countries. For R&D in the food industry, the study showed that spending in recent years was higher than for agricultural R&D. Between 1990 and 2012, private sector food manufacturing R&D spending worldwide almost tripled, rising from 6.4 billion to 18.7 billion 2005 PPP dollars (Table 4).

Regarding the allocation of private sector R&D expenditures to specific countries or world regions, Fuglie (2016) estimated that 87 percent of the 12.9 billion 2005 PPP dollars invested in agricultural R&D was from companies whose headquarters were in high-income countries, and 13 percent from those based in other countries. However, even for companies based in high-income countries, some of the R&D spending will be in other countries.

Figure 1. Public sector agricultural R&D spending in high-income OECD countries over time



Source: Adapted from Heisey, P.W. & Fuglie, K.O. 2018b. *Agricultural research investment and policy reform in high-income countries.* Economic Research Service Report 249. Washington D.C., U.S. Department of Agriculture (USDA). Table 3.1. www.ers.usda.gov/webdocs/publications/89114/err-249.pdf

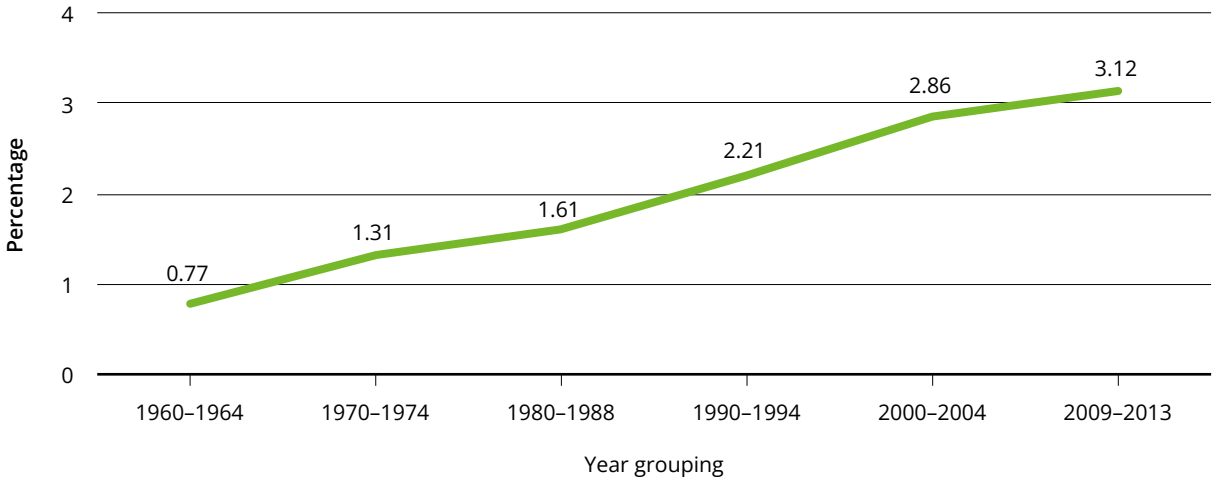
To investigate the issue, he analysed the top 23 companies, all of which had headquarters in high-income countries. Assuming that they allocate their R&D spending around the world in proportion to the regional sales of agricultural inputs, he estimated that 28 percent of their agricultural R&D was in Argentina, Brazil, China, India, Mexico, South Africa, Türkiye and developing countries.

2.3 USDA-ERS work on public sector agricultural R&D spending in high-income OECD countries

Heisey and Fuglie (2018a, 2018b) built a comprehensive time series from 1960 (or later for three countries) to 2013 of public agricultural R&D spending for 31 high-income OECD countries. For data after 1980, their main data source was the OECD Main Science and Technology Indicators database. More information is provided in the Annex. Their results show that public spending on agricultural R&D increased substantially in high-income OECD countries from 1960 onwards (Figure 1). For the years 1960, 1970, 1980, 1990, 2000 and 2010, spending was 3.9, 8.2, 11.2, 14.5, 16.9 and 18.5 billion 2011 PPP dollars respectively. Following the global financial crisis in 2008-09, spending fell. From 2010, investments declined to reach 17.5 billion 2011 dollars in 2013.

Figure 2 shows that ARI estimates followed a similar pattern – rising from 0.77 percent in the 1960–1964 period to 1.61 percent in 1980–1988 and 3.12 percent in 2009–2013. They peaked at 3.6 percent in 2009 and declined thereafter, descending to 2.74 percent in 2013. Heisey and Fuglie (2018b) show that the ARI is higher than the research intensity for total public research (investments in public sector research/ GDP), which was 0.79 percent in 2009–2013. They argue that this can be attributed to the relatively low proportion of private R&D

Figure 2. Evolution of the agricultural research intensity in high-income countries over time



Source: Adapted from Heisey, P.W. & Fuglie, K.O. 2018b. *Agricultural research investment and policy reform in high-income countries*. Economic Research Service Report 249. Washington D.C., U.S. Department of Agriculture (USDA). Table 4.2. www.ers.usda.gov/webdocs/publications/89114/err-249.pdf

spending in the agriculture sector compared to other sectors; the fact that agriculture is a technology-dependent sector; and that public sector agricultural R&D investments also address a broad range of non-production issues like environmental concerns, food safety and nutrition.

With their estimates of public sector spending in high-income OECD countries, Heisey and Fuglie (2018a, 2018b) also estimated the total amount of global investments in agricultural R&D in 1990 and 2011. For public sector spending in other countries, they used data from ASTI. For the private sector, they used data from Fuglie (2016), but converted to 2011 PPP dollars instead of 2005 PPP dollars to allow for direct comparison. From Fuglie (2016), they used the data for the seven agricultural input sectors and for the food manufacturing sector separately.

The results show that the total agricultural R&D spending increased from 32.8 to 56.6 billion 2011 dollars from 1990 to 2011 (Table 5). For the public sector, spending in high-income OECD countries increased from 14.5 to 18.2 billion 2011 PPP dollars in this time period, while it increased even more, from 10.7 to 24.1 billion 2011 PPP dollars, for the other countries.

For the private sector, increases between 1990 and 2011 were also very substantial, from 7.6 to 14.3 billion 2011 PPP dollars. The proportion of spending by the private sector increased from 23 to 25 percent from 1990 to 2011. Note that the private sector data in Table 5 includes only R&D in the seven agricultural input areas relating to crops, animals and farm machinery. If spending on food manufacturing/processing R&D was included, this would bring the total private sector investments to 15.0 and 33.6 billion 2011 PPP dollars for 1990 and 2011 respectively, and the private sector share of total investments would increase from 37 to 44 percent for these years.

Table 5. Public and private sector spending on agricultural R&D (in billion 2011 PPP dollars and percentages for specific years)

	Billion 2011 PPP dollars		Percentages	
	1990	2011	1990	2011
Public				
High-income OECD countries	14.5	18.2	44	32
Other countries	10.7	24.1	33	43
Total	25.2	42.3	77	75
Private	7.6	14.3	23	25
All investments	32.8	56.6	100	100

Source: Adapted from Heisey, P.W. & Fuglie, K.O. 2018b. *Agricultural research investment and policy reform in high-income countries.* Economic Research Service Report 249. Washington D.C., U.S. Department of Agriculture (USDA). Figure 1.1. www.ers.usda.gov/webdocs/publications/89114/err-249.pdf

Note: Private sector data do not include food manufacturing

2.4 InSTePP work on global public and private sector food and agricultural R&D spending

Building on earlier versions from 2009 and 2012, the International Science and Technology Practice and Policy (InSTePP) developed a database spanning the period from 1960 to 2011, including both public and private sector investments in food and agricultural R&D, which is amply documented by Pardey *et al.* (2016a). More details are available in the Annex.

For public sector research expenditures, the main sources of data over the period from 1960 to2011 for low- and middle-income countries were the International Service for National Agricultural Research publications for older data, and ASTI in later years. For high-income countries, they drew on several sources, including national data and OECD databases.

For private sector research expenditures, they built a dataset to cover the 1980–2011 period. For the United States of America, primary data were collected and a purpose-built series using firm-level data was constructed. For 34 other high-income countries and territories, estimates drew heavily on OECD sources, particularly the ANBERD database. Here, they included all R&D spending they considered relevant to food and agriculture from the database, including all investments in “food, beverages and tobacco” and “agriculture, hunting and forestry”, and a small proportion of spending allocated to the “machinery” and “chemical and pharmaceutical” sectors (industries). For some major middle-income countries, they used national data sources. For the remaining low- and middle-income countries, in the absence of country-level data, they used an econometric model to estimate their private sector research spending.

Using the database, a global overview of food and agriculture R&D spending was presented by Pardey *et al.* (2016b) and, in more detail, by Pardey *et al*. (2018). The overview covered 130 countries/ territories for the public sector and 128 for the private sector. The results showed that global investments in both public and private food and agricultural R&D investments have increased over time (Table 6). For the years 1980, 1990, 2000 and 2011, they estimated that global investments were 27.4, 37.0, 46.3 and 69.3 billion 2009 PPP dollars respectively.

In 2011, an estimated 38.1 billion 2009 PPP dollars were spent on public sector R&D and 31.2 billion 2009 PPP dollars on private sector R&D. In that same year, high-income countries invested 37.9 billion 2009 PPP dollars (with slightly more coming from the private sector than the public sector), middle-income countries invested 30.1 billion 2009 PPP dollars (about two-thirds from the public sector) and low-income countries invested 1.3 billion 2009 PPP dollars (almost all public sector).

Their results show that, over time, the relative investments made by high-income and middle-income countries have changed substantially. In 1980, 69 percent of the world's food and agricultural R&D took place in high-income countries (Table 7). By 2011, this had fallen to 55 percent. For middle-income countries, on the other hand, their global share rose from 29 percent in 1980 to 43 percent in 2011. Looking at the public sector alone, the high-income countries' spending rose from 10.9 to 18.0 billion 2009 PPP dollars from 1980 to 2011, while it rose much faster, from 6.4 to 19.0 billion 2009 PPP dollars, for middle-income countries (Table 6).

Total R&D investments in low-income countries rose slightly, from 0.7 to 1.3 billion 2009 PPP dollars from 1980 to 2011, but the levels remain extremely low (2 percent of the total). Estimated private sector investments in these countries were very small, representing just 0.1–0.4 percent of the total R&D investments for a given year.

Private sector investments in food and agricultural R&D are increasing faster than public sector investments. From 1980 to 2011, the proportion of total investments attributed to the private sector rose from 35 to 45 percent. In high-income countries, they rose from 8.0 to 19.9 billion 2009 PPP dollars (i.e. more than doubled) over the same time period, while in middle-income countries they jumped from 1.5 to 11.1 billion 2009 PPP dollars (an over seven-fold increase).

Estimates for private sector research expenditures come mainly from the OECD ANBERD database, using data from four different sectors (industries). Pardey *et al*. (2018) report that the analysis of private sector R&D spending by 26 high-income countries for which sector-specific data were available indicated that investments were consistently greatest in the "food, beverages and tobacco" sector. For the years 1980, 1990, 2000 and 2011, they represented 50, 51, 48 and 44 percent respectively of the total private sector R&D spending. In 2011, 37 percent of the private sector R&D investments were related to "agriculture and chemicals", while 19 percent was related to "machinery".

Table 6. Public sector, private sector and total spending on food and agricultural R&D (in billion 2009 PPP dollars)

Grouping	1980	1990	2000	2011
Public				
High-income countries	10.9	13.8	16.5	18.0
Middle-income countries	6.4	8.25	10.6	19.0
Low-income countries	0.6	0.75	0.9	1.1
Total	17.8	22.8	27.95	38.1
Private				
High-income countries	8.0	12.1	15.4	19.9
Middle-income countries	1.5	2.05	2.8	11.1
Low-income countries	0.1	0.05	0.1	0.2
Total	9.6	14.2	18.35	31.2
Total				
High-income countries	18.9	25.9	31.9	37.9
Middle-income countries	7.9	10.3	13.4	30.1
Low-income countries	0.7	0.8	1.0	1.3
All investments	27.4	37.0	46.3	69.3

Source: Pardey, P.G., Chan-Kang, C., Dehmer, S.P. & Beddow, J.M. 2016b. Agricultural R&D is on the move. *Nature* 537, 301–303. www.nature.com/news/agricultural-rd-is-on-the-move-1.20571. [Public sector and total R&D data adapted from Table A4 and Table A1 (supplementary data) respectively; while the private sector R&D data are derived by subtracting the public sector investments from the total R&D.]

2.5 Main common results

While different base years and datasets might have been used, some clear and common key trends emerge from the different analyses that have been carried out on investments in agricultural R&D worldwide:

- Investments in agricultural R&D are increasing;
- The share of investments by middle-income countries is increasing and the share of investments by high-income countries is decreasing;
- Spending in low-income countries continues to be extremely low;
- There are major inequalities in investments worldwide – over half of the global spending is by a handful of countries; and
- Investments by the private sector are becoming more important.

Table 7. Public sector, private sector and total spending on food and agricultural R&D (as percentages for specific years)

Grouping	1980	1990	2000	2011
Public				
High-income countries	40	37	36	26
Middle-income countries	23	22	23	27
Low-income countries	2	2	2	2
Total	65	62	60	55
Private				
High-income countries	29	33	33	29
Middle-income countries	6	6	7	16
Low-income countries	0.4	0.1	0.2	0.3
Total	35	38	40	45
Total				
High-income countries	69	70	69	55
Middle-income countries	29	28	30	43
Low-income countries	3	2	2	2
All investments	100	100	100	100

Source: Pardey, P.G., Chan-Kang, C., Dehmer, S.P. & Beddow, J.M. 2016b. Agricultural R&D is on the move. *Nature* 537, 301–303. www.nature.com/news/agricultural-rd-is-on-the-move-1.20571. [Public sector and total R&D data adapted from Table A4 and Table A1 (supplementary data) respectively; while the private sector R&D data are derived by subtracting the public sector investments from the total R&D.]

3. Discussion

3.1 Data availability

The small number of groups who work in this field do a painstaking and complicated job trying to bring together and analyse data on investments in agricultural R&D. There are, however, considerable data limitations. In many cases, data are missing so they are forced to use approximate methods to estimate investments.[11] The ARI-AgGDP approach is the most common method.

3.1.1 Public sector data

For public sector R&D investments in low- and middle-income countries, ASTI has played a unique and essential role in carrying out national surveys and generating primary data. Even then, however, the surveys do not cover all low- and middle-income countries and so, for many, investments are estimated using the ARI-AgGDP approach.

Regarding public sector R&D investments in high-income countries, contrary to what one might expect, the quality of data available is often poorer than that of many low- and middle-income countries. For example, the Impact of Research on EU Agriculture (IMPRESA) project, in which FAO participated, looked at investments (public and private sector) in agricultural research in 20 European Union (EU) countries.

Among its key findings on this subject, Chartier, Stads and Midmore (2015, p. 5) state:

> **Despite the existence of standardised definitions and methodologies for the production of statistics on R&D, the available data do not permit adequate monitoring of agricultural research expenditures in Europe. There are far too many gaps in national, European (EUROSTAT) and international (OECD) databases.**

The work on public sector R&D investments described in this report has focused on research by national institutions. There are, however, additional investments, albeit relatively moderate, being made by international agricultural research centres. These include the Association of International Research and Development Centers for Agriculture (AIRCA), an alliance of seven centres worldwide whose combined annual budget is currently near USD 0.2 billion. It also includes the CGIAR with over 9000 scientists, technicians and staff working in its 15 research centres worldwide. Beintema and Echeverria (2020, Table 1) estimated that CGIAR spending was almost 1 billion 2011 PPP dollars in 2014. Adding these figures to those from Table 3 indicates that the total global expenditure on agricultural research worldwide was about 60.5 billion 2011 PPP dollars in 2014, comprising an estimated 45.0 billion 2011 PPP dollars (74 percent) from the public sector and 15.5 billion 2011 PPP dollars (26 percent) from the private sector.

11 This is evident by looking at the data sources for countries from Beintema et al. (2012) at www.asti.cgiar.org/pdf/CountrySourcesEstimations.pdf; Beintema, Nin Pratt and Stads (2020) at www.asti.cgiar.org/pdf/Country-Data-Sources-and-Estimation2020.pdf and the relevant tables with country data sources in Pardey et al. (2016a).

3.1.2 Private sector data

Regarding the private sector, evidence suggests that official national data on private sector spending in agriculture-related R&D often tend to be insufficient, if they exist at all, and of poor quality (Chartier *et al.*, 2015; Doghmi *et al.*, 2015; Fuglie, 2016; Fuglie, Clancy and Heisey, 2018). The compilation of private sector data also presents some specific challenges. One is how to capture spending from private sector companies that are normally classified in databases as working in a non-agricultural area (e.g. production of chemicals) but also dedicate some of their products to agriculture. Another is how to gather data on national private sector R&D expenditures for multinational corporations operating in many countries.

One way to overcome this problem is to build a database with the spending of individual companies. This was the approach used by Fuglie *et al*. (2011, 2012) and Fuglie (2016), whose database included 324 leading companies worldwide in seven specific areas of agricultural inputs. This was also the approach used by InSTePP researchers who constructed (Pardey *et al.*, 2016a, 2016b) and expanded (Chai *et al*., 2019; Lee, 2019) a database of spending by food- and agriculture-related firms in the United States of America to get an estimate of private sector R&D investments in the country. The InSTePP firm-level database contains 408 companies operating in the United States of America between 1950 and 2014 (Lee, 2019). Food-related firms include those engaged in processing and producing food, beverages and tobacco products while agriculture-related firms include those involved in manufacturing farm machinery, seed production and agricultural chemicals.

One of the disadvantages of using a firm-based approach to estimate private R&D investments is that it may exclude investments made by smaller companies, especially in low- and middle-income countries. It may also exclude R&D investments by startup companies funded by venture capital (VC) which are operating in this area. Fuglie (2016) suggests there has been a sharp rise in VC funding for small and medium enterprises in food and agriculture in recent years. From annual investment reports, he estimated that USD 6.9 billion (nominal) were invested by VC funds based in the United States of America in food and agriculture in the 2014 to 2015 period. He estimated that USD 3.0 billion were directed to food startups, USD 2.6 billion to agriculture and USD 1.3 billion to new uses of agricultural commodities, such as bioenergy. Food e-commerce marketing and precision agriculture were the areas receiving most investments.

Graff, Silva and Zilberman (2021) highlighted the important role of VC investments in R&D-intensive startup companies in agriculture. They compiled a global dataset of 4552 startup agricultural technology companies founded from 1977 to 2017, identified from three proprietary business databases. Most were in the United States of America (1483, i.e. 33 percent) and the European Union (1063, 24 percent), followed by Canada (228, 5 percent), India (210, 5 percent), China (172, 4 percent), Brazil (88, 2 percent) and South Africa (41, 1 percent). Over half of the startups were involved in some form of agricultural input technology or service – the two largest areas were software and data (942 startups) and biotech, genetics or health (918 startups). They also analysed a subsample of 1367 startups (29 percent of the total) for which data were available regarding financial transactions. This analysis indicated that until 2006, the amounts invested in agricultural startups globally were relatively small, typically less than USD 200 million per year, but they grew steadily thereafter and

increased rapidly after 2012. Although it is hard to estimate what proportion of such investments are dedicated to agricultural R&D as defined by the *Frascati Manual*, they are obviously providing an additional source of food and agricultural R&D funding from the private sector which is normally not documented.

3.2 Methodological issues

Most of the work done on gathering agricultural R&D data and their subsequent analysis is based on similar approaches. As described in Section 2 and the Annex, they are all based on procedures described in the *Frascati Manual* (OECD, 2015); the research data are gathered on a "by performer" basis (i.e. allocated to the body doing the research rather than to the one funding it); they aim to gather data based on the purpose of the research rather than the content of the research (something which, unfortunately, the data often do not allow); they aim to be cross-sectoral, including crops, livestock, forestry and aquaculture; and spending is adjusted for inflation and compared across countries using the "deflate and convert" approach.

3.2.1. Food processing/manufacturing R&D

One important difference regards whether investments should include food processing/manufacturing R&D. ASTI (2016) notes that they also included research concerning the on-farm storage and processing of agricultural products but did not include R&D in the agrochemical industry, agricultural machinery, and the food processing industry off-farm.

To compile data on private sector investments, Fuglie (2016) and Fuglie *et al*. (2011, 2012) built up a database of leading firms working in seven major input areas – seeds and biotechnology, agricultural chemicals and crop nutrition (for crops), breeding, health and nutrition (for animals) and farm machinery. They did not include food manufacturing/processing as they argue that R&D in this area will not help to increase agricultural productivity and improve food security or people's livelihoods. The food and beverage manufacturing sector transforms raw agricultural materials into intermediate foodstuffs, animal feed or edible products. Although the available data do not indicate which areas of research are prioritized by firms in the food manufacturing sector, Fuglie *et al*. (2011) consider the issue and infer that most of the R&D carried out in this area seems to be directed towards the development of new food products (such as chicken nuggets) rather than new processes to reduce manufacturing costs. They conclude that this research will not directly affect production or productivity at the farm level for the farmer.

Pardey *et al*. (2016a, 2016b), on the other hand, specifically include estimates of "food, beverages and tobacco" R&D with those of private sector agricultural R&D (from the OECD ANBERD database). They justify inclusion of food processing based on their interpretation of the *Frascati Manual*, noting that different sources use different guidelines for handling food, beverages and tobacco processing R&D investments. Furthermore, they indicate that some estimates of public agricultural R&D spending are aggregates which also include investments in research related to food processing. For more details on these issues, see Pardey *et al.* (2016a, pages 4–5).

Private sector R&D investments in food manufacturing/processing are substantial and increasing, which contributes to explain why the estimates and share of private sector R&D spending from InSTePP (Tables 6 and 7) are higher than those from analyses which aim to exclude the food manufacturing sector (Tables 3 and 5).

3.2.2. Use of the "deflate and convert" approach

A major challenge, which is common to all the groups working in this area, is how to correctly compare spending made in agricultural R&D in different currencies, years and countries worldwide. As described earlier, this is normally done using the "deflate and convert" approach, where spending within a country is first adjusted for inflation and expressed relative to a chosen base year and then converted to a common currency to allow for international comparisons. Most expenditures in agricultural research relate to salaries, typically accounting for 60 to 70 percent of the total, and the remainder goes to operating expenses and capital costs (Pardey and Beintema, 2001; Roseboom, 2002; Heisey and Fuglie, 2018b).

To account for inflation, GDP deflators, normally from the World Bank's WDI database, are used. However, ideally, research-specific deflators should be used as these may differ from the national GDP deflators. Chai *et al*. (2019) report that InSTePP keeps an R&D-related price index for the United States of America and that the prices rose higher than indicated by the GDP deflators because scientists' salaries increased more than the overall rate of inflation.

How spending in different countries is converted to a common base can also influence the results substantially (Roseboom, 2002; Pardey *et al*., 2018). For example, Pardey and Beintema (2001) illustrate the impact of using market exchange rates to convert spending from different countries to United States dollars instead of using PPP exchange rates to convert spending to international dollars. When market exchange rates are applied, the funds used for research in countries with high prices are overstated. Their results showed that, using market exchange rates, a much greater share of global agricultural R&D expenditures was apportioned to rich countries than when PPP exchange rates were used.

Use of PPP exchange rates, normally from the World Bank's WDI database, has been the method of choice for conversion as they, *inter alia*, express the relative purchasing power of different currencies using the local prices of a common basket of local goods and services. However, ideally, exchange rates that are specifically developed for agricultural research should be applied, although it is complicated to do. When this is done, it can have a sizeable effect on the results (e.g. Heisey & Fuglie, 2018a, 2018b; Chai *et al.*, 2019).

Heisey and Fuglie (2018a, 2018b) built a simplified agricultural R&D price index for the 1992–2012 period for seven high-income countries (Australia, Canada, France, Germany, Japan, the United Kingdom of Great Britain and Northern Ireland, and the United States of America) using university faculty salaries for the costs of scientific labour and assuming that 70 percent of the total agricultural R&D expenses were due to scientific labour. They also assumed that the remaining 30 percent were due to non-labour R&D inputs and that these costs rose over time at the same rate as the GDP price index. They found that the cost of agricultural R&D rose higher in the period from 1992 to 2012 than the GDP deflators in all countries (although more in some, such as the United Kingdom, than others, like Germany). They note that this issue is not specific to agricultural R&D but has also been found for other kinds of R&D because, being a highly specialized branch of work, salaries tend to grow more than the normal rate of inflation. When the usual GDP deflators were used, they found that the total spending on

agricultural R&D for these seven countries showed a modest increase between 1992 and 2012. However, using their R&D price index, they found that the spending on agricultural R&D showed no growth in this time period.

For international comparisons of these seven countries, Heisey and Fuglie (2018a, 2018b) used scientific labour costs for the different countries (taken to be 70 percent of the total costs) and assumed that the cross-country relative values of non-labour costs (30 percent of the total) were the same as the PPP exchange rate from the World Bank's WDI database. They thus created "alternative PPP exchange rates" that specifically took account of the costs of scientific labour in the different countries. They found that scientific labour costs in the United States of America were higher than those in five of the other six countries, which implies that R&D spending in these five countries, relative to spending in the United States of America, was increased compared to using the usual PPP exchange rates. For example, France's spending was originally 30 percent of that in the United States of America but it increased to about 38 percent using the "alternative PPP exchange rates".

Using GDP deflators and PPP values from the World Bank's WDI database, Heisey and Fuglie (2018a, 2018b) found that the total R&D spending in the seven countries increased from 11.0 to 12.4 billion 2011 PPP dollars from 1992 to 2012. However, using R&D-based price indices and exchange rates, they found that the total R&D spending in the seven countries decreased from 13.9 to 13.6 billion 2011 PPP dollars from 1992 to 2012.

Given their apparently important influence on international trends in agricultural R&D investments, more work is needed on R&D-based price indices and exchange rates.

3.3 Overall spending in agricultural research increasing over time

As seen from the results summarized in this paper, spending on agricultural R&D has increased in recent decades, both for the public sector and, particularly, the private sector. Agricultural research spending per capita has also increased, despite the substantial growth in the world's population over this time. For example, total spending from 1990 to 2014 increased by 77 percent (Table 3) while the global population increased by 37 percent over the same period.

However, it can be strongly argued that the need for agricultural R&D is far greater now than it was in the past because of the tremendous challenges facing the planet and the broader range of research areas that need to be addressed. The global population is still increasing and there is continued degradation of natural resources, such as soil and water resources, upon which agriculture depends. Climate change is a reality and is affecting all aspects of food and agricultural production. Food insecurity continues to plague humankind and the number of undernourished people is increasing. The need for access to healthy diets is also increasingly recognized as the number of people who are overweight and obese rises in all parts of the world.

We are also living in a more technology-driven world now than before where advances in science, technology and engineering, which require extensive amounts of R&D, are changing the way we live and how we work. The National Science Board (2022) estimated that global investments in R&D have more than tripled from 2000 to 2019, from 725 billion to 2.4 trillion PPP dollars respectively, not adjusted for inflation. Dehmer *et al*. (2019) estimated that global

R&D rose over three-fold from 1980 to 2013, from 479 billion to 1.61 trillion 2009 PPP dollars respectively, adjusted for inflation. So, although the tables presented in this report show that agricultural research spending has increased globally in recent decades (for example, Table 3 shows a 77 percent rise from 1990 to 2014), the evidence indicates that investments in all forms of R&D have risen even faster over the same time period. This is also supported by recent unpublished InSTePP results indicating that the share of food and agricultural R&D in the total global R&D has declined from 8 to 5 percent from 1981 to 2015 (cited in Alston, Pardey and Rao, 2020). Heisey & Fuglie (2018b) document the same trend and note that the declining share of agricultural research as a percentage of total public research spending is a consequence of the declining importance of agriculture for national economies.

3.4 Change in share of total spending by high- and middle-income countries

Results from the different analyses presented here show that spending on agricultural R&D in high-income countries has increased in recent decades but at a much slower rate than in middle-income countries. As a result, the share of total agricultural R&D has declined in high-income countries and increased in middle-income countries. The slower increase in high-income countries can be due to several factors, including the declining importance of agriculture for the GDP, the perception that food insecurity is no longer an issue in these countries and the belief that growing private sector investments in agriculture will fill the gaps of government spending.

The increasing share of research investments by middle-income countries over time reflects the increasing share of agricultural production by these countries. Alston, Pardey and Rao (2021) estimate that the relative share of global agricultural production, measured in 2016 PPP dollars, declined from 44 to 24 percent in high-income countries from 1961 to 2016 while it increased in middle-income countries from 56 to 76 percent in the same time period. For middle-income countries, the major growth in research spending comes from a small number of countries such as India, Brazil, and especially China.

The strength of this trend is also shown by Chai *et al*. (2019) from InSTePP who compared public and private sector food and agriculture R&D investments in China and the United States of America from 1950 to 2013. For China, they indicate that the data are updated and incorporate some revisions of the estimates previously reported by Pardey *et al*. (2016b, 2018). For the United States of America, they report that they revised and updated the data series developed by InSTePP (Pardey *et al*., 2016a), including public sector data from the United States Department of Agriculture and, for the private sector, updating and revising the firm-level database used previously. Using these data, they estimated that the total food and agriculture R&D investments in China exceeded those in the United States of America in 2010 and that by 2013 China spent considerably more than the United States of America in both the public sector (5.7 versus 4.0 billion 2011 PPP dollars) and the private sector (12.7 billion versus 9.1 billion 2011 PPP dollars).

These trends regarding the changing share of investments by high- and middle-income countries in agricultural R&D are also evident when all kinds of R&D, i.e. not just agricultural R&D, are examined. Looking at specific years from 2007 to 2018, the share of total R&D, expressed in 2005 PPP

dollars, decreased progressively from 80 to 64 percent for high-income countries and increased from 20 to 36 percent for middle-income countries (Soete *et al*., 2015; Schneegans, Lewis and Straza, 2021). Most of this increase was due to China, whose contribution to the global total rose from 10 to 25 percent from 2007 to 2018.

Results synthesized in this report show that a small number of high- and middle-income countries dominate, with nine of them (China, the United States of America, India, Brazil, Japan, the Islamic Republic of Iran, France, Germany and the Republic of Korea) accounting for almost 60 percent of the world's total public agricultural research in 2016 (Beintema, Nin Pratt and Stads, 2020). This finding is not unique to agricultural research as, looking at all kinds of research together, these same nine countries accounted for an estimated 74 percent of global R&D spending in 2011 (Soete *et al*, 2015) and 78 percent in 2018 (Schneegans, Lewis and Straza, 2021).

3.5 Low spending in low-income countries

The results summarized here indicate that little has changed regarding agricultural R&D investments in low-income countries in recent decades. Spending has increased marginally over time, but it has remained at a meagre 2 percent of the total in these countries, which currently account for about 10 percent of the global population and are highly vulnerable to climate change and the most exposed to the problems of food insecurity and hunger. A similar trend is found when looking at all kinds of R&D, where low-income countries' share of total R&D expenditures in specific years from 2007 to 2018 ranged from 0.1 to 0.3 percent (Soete *et al*., 2015; Schneegans, Lewis and Straza, 2021).

While levels of investments in agricultural R&D are low, another challenge in low-income countries is volatility of investments because they may fluctuate from year to year. Angelico *et al*. (2015) looked at the distribution of official development assistance (ODA) to agricultural, forestry and fishery research among the top ten recipient countries during the period from 2002 to 2012 and found that allocations fluctuated widely over the years. Beintema (2020b) used ASTI data to examine volatility in research funding for 36 sub-Saharan African countries over the period from 2000 to 2016. She found that funding was often highly volatile, noting that it prevents agricultural research organizations from planning and budgeting appropriately; attracting, maintaining and motivating well-qualified researchers; and, ultimately, carrying out research effectively. Stable funding is very important. Rawat (2020) used ASTI data, supplemented by OECD and United Nations Educational, Scientific and Cultural Organization (UNESCO) data when not available, to analyse volatility in public R&D spending in 112 countries from 1981 to 2014. She found that volatility was highest in low-income countries and the sub-Saharan region. She suggested some approaches for countries to use to address volatility, including development of a long-term national R&D strategy and increased coordination of decision-making between national R&D agencies.

To achieve the SDGs, emphasis should be given to increasing investments and strengthening the national agricultural research systems (NARS) in low-income countries. This is also important because spillovers from R&D in non-agricultural areas, such as artificial intelligence, human genetics, robotics and renewable energy, can have big impacts on agriculture. Spillovers will be increasingly important for agricultural research as the vast majority of R&D spending

is currently dedicated to non-agricultural areas and the proportion of total R&D spending dedicated to agriculture is relatively small and declining. An analysis by Fuglie (2018) indicates that countries with stronger national R&D capacities are more likely to benefit from R&D spillovers across national borders, thus highlighting the importance of capacity building in low-income countries so they can benefit from potentially appropriate spillovers.

Given the relatively low levels of investments in low-income countries, regional initiatives should also be strengthened so that countries can benefit from synergies and make more cost-efficient use of scarce national R&D resources. Partnerships in agricultural research also need to be strengthened so that low-income countries can benefit from South–South, North–South and triangular cooperation. Cooperation with the CGIAR can be particularly important here. Although its annual R&D budget is relatively moderate (normally below USD 1 billion) compared to the global total, it has a long history of working with NARS in low-income countries and is able to leverage R&D capacity in high- and middle-income countries for the benefit of low-income countries (Alston, Pardey and Rao, 2020).

3.6 The increasing importance of the private sector

The results synthesized in this paper indicate that agricultural R&D spending by the private sector is rising faster than the public sector, so its share of the global agricultural research is increasing. The latest global figures from 2014 (Table 3) indicate that roughly one-quarter of all agricultural R&D is private. This is likely to be higher in practice because it does not include, *inter alia*, estimates of R&D investments by VC-funded startups. Spending on food manufacturing/processing R&D is increasing fast. When combined with agricultural R&D, estimates indicate that the private sector share of the total food and agricultural R&D investments increased from 38 to 45 percent from 1990 to 2011 (Table 7).

It is very encouraging that the private sector is investing more in agriculture and agricultural research. This augurs well for the future. The average age of farmers is increasing (FAO, 2018; Lowder, Sánchez and Bertini, 2019). For young people to be more involved in agriculture, they need to see that agriculture will be profitable and more like a business that can provide them with a livelihood. The increasing involvement of the private sector can make this happen.

Although the private sector is investing more in agricultural research, it is nevertheless essential that investments in public research also increase. This is because public sector research organizations can focus on certain research areas without being guided by the necessity to make an economic profit. These include research areas involving public goods, and covering topics such as environmental protection, food safety, sustainability and climate change. Private sector R&D tends to focus on the needs of larger, more economically stable, farmers, and on a limited number of commodities, where a sizeable market exists and profits are likely. The public sector plays an essential role in carrying out research on crop and animal species that are not prioritized by the private sector, such as roots and tubers, and small ruminants (Fuglie, 2016). The analysis by Beintema (2020a) of the research focus areas of public sector researchers in 83 low- and middle-income countries clearly shows the wide diversity of commodities and research topics that they cover.

Private companies are often reluctant to invest in developing countries because of less developed value chains, the high costs of serving small remote farms, and other factors (FAO, 2014). Public sector research organizations can play an important complementary role to the research-oriented private sector companies through their focus on basic science and their contribution to building national scientific and technical capacities (Fuglie *et al*., 2012). The existence of a strong public agricultural research system in a country can be an important incentive for private sector companies to invest in research there.

Another important reason for increased public sector investments is that the private sector in food and agriculture is becoming increasingly consolidated, with a few companies having a large amount of power and control of the market. Fuglie *et al.* (2011) examined seven agricultural input sectors and concluded that in most of them, market concentration increased from 1994 to 2009, with the highest levels observed in the animal breeding and crop seed sectors. Fuglie (2016) listed the top 110 companies in these seven sectors that spent at least USD 10 million in R&D in 2014, estimating that just eight of them were responsible for over half of the total agricultural R&D. In their analysis of the seed sector, IHS Markit Agribusiness Consulting (2019) showed that the top three companies accounted for over 50 percent of the global commercial seed market in 2018 and the top ten companies accounted for almost 70 percent of the market.

The Global Sustainable Development Report (Messerli *et al*., 2019) identified concentration of ownership as one of five immediate barriers to transitioning to sustainable food systems, because it could reduce the resilience of the global food system and be an impediment to small-scale farmers. Fuglie *et al*. (2012) argued that the situation where a few firms dominated global market sales – accounted for most of the private sector R&D spending – and hold large patent portfolios could create barriers to the entry of new firms and limit market competition. Among the measures proposed by Clapp (2021) to ensure that corporate concentration and power do not undermine key goals for food systems, she includes governments providing broader support for public sector agricultural research that encourages innovation that is not driven solely by profit. It is therefore important to have a thriving well-funded public agricultural R&D system.

4. Conclusions and recommendations

Measuring and monitoring expenditures in agricultural research is very important for evidence-based policymaking, and this area of work should be given long-term support. Information provided by such analyses, such as the status and trends in agricultural research spending at the global, regional and national levels, and the related sources of such funding, is fundamental for policymakers needing to make decisions regarding the allotments of funding to science, technology and innovation.

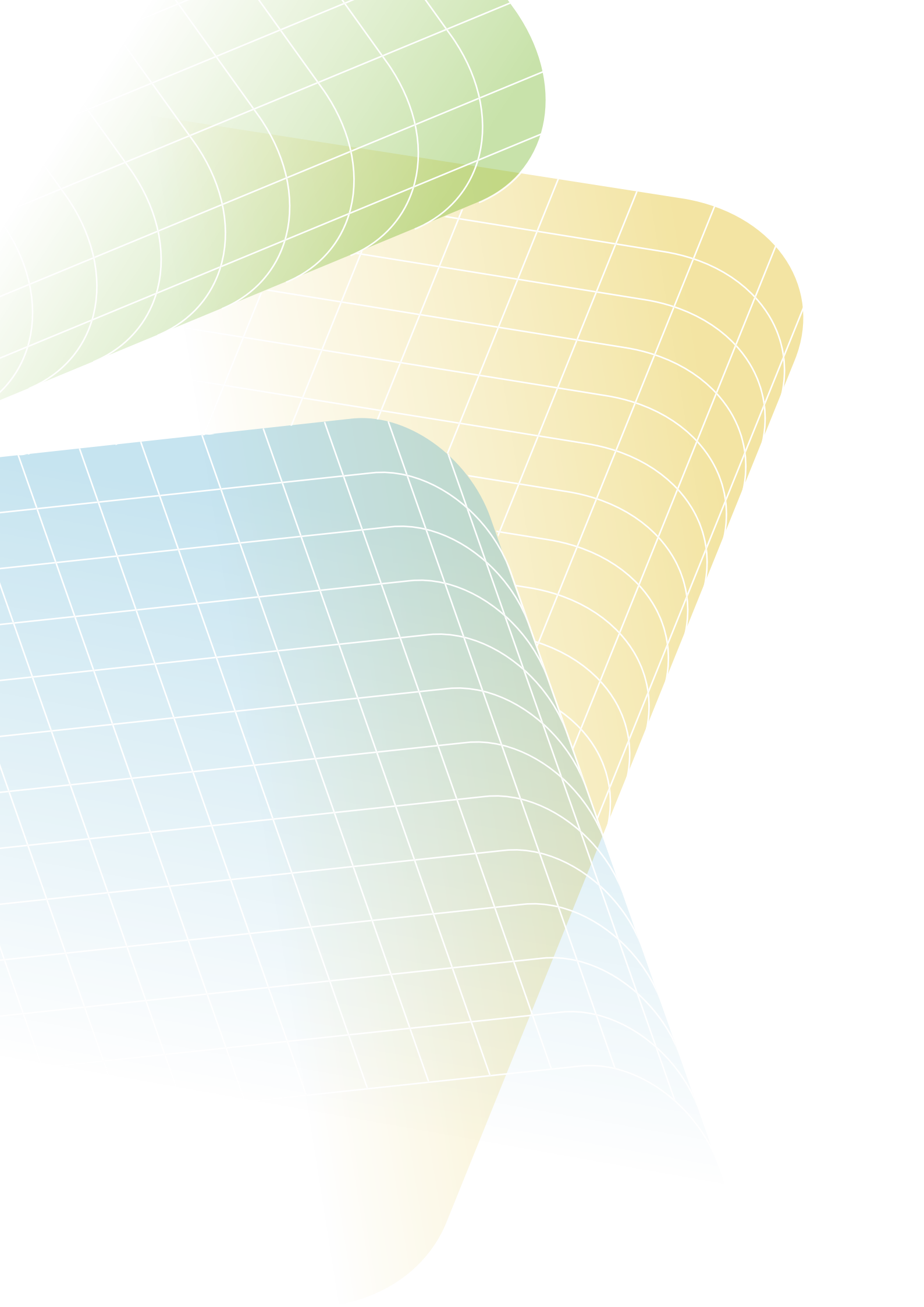
The small number of people/groups who work in this field do a complicated and painstaking job when measuring and monitoring expenditures in agricultural research. Getting an accurate overview of the current status and trends regarding global investments in agricultural research is not easy because data are often missing and, when available, they may not be of good quality. There is a need to improve the quality of available data so that more accurate monitoring of agricultural R&D trends is possible.

Despite this, some clear results emerge from studies on global investments in recent years:

- Global spending on agricultural R&D continues to grow, although at a slower rate than for total R&D spending.
- The relative contribution of agricultural R&D spending by high-income countries is declining while it is increasing in middle-income countries.
- Spending in low-income countries continues to be extremely low.
- There are tremendous inequalities in spending worldwide, with most investments being made by a handful of countries.
- Investments by the private sector are growing at a faster rate than the public sector.

Investing in agricultural R&D is central to achieving the SDGs, particularly SDGs 1 and 2. In this context, the low levels of investments dedicated to agricultural R&D in low-income countries, where rural poverty and food insecurity are greatest, need to be increased and their national agricultural research systems need to be strengthened. Stability of funding also must be ensured. In addition, regional initiatives should be strengthened so that low-income countries can benefit from synergies and make more cost-efficient use of scarce resources. Partnerships in agricultural research should also be strengthened so that low-income countries can benefit from South–South, North–South and triangular cooperation. Partnerships with the CGIAR can be particularly important here.

While it is very encouraging that the private sector is investing more in agricultural research, it is essential that investments in public research continue to increase, as research carried out by the private sector will not replace public sector research, particularly research aiming to improve the sustainability of food systems and enable smallholders and family farmers to deal with the many challenges they face, including climate change and improving their livelihoods.



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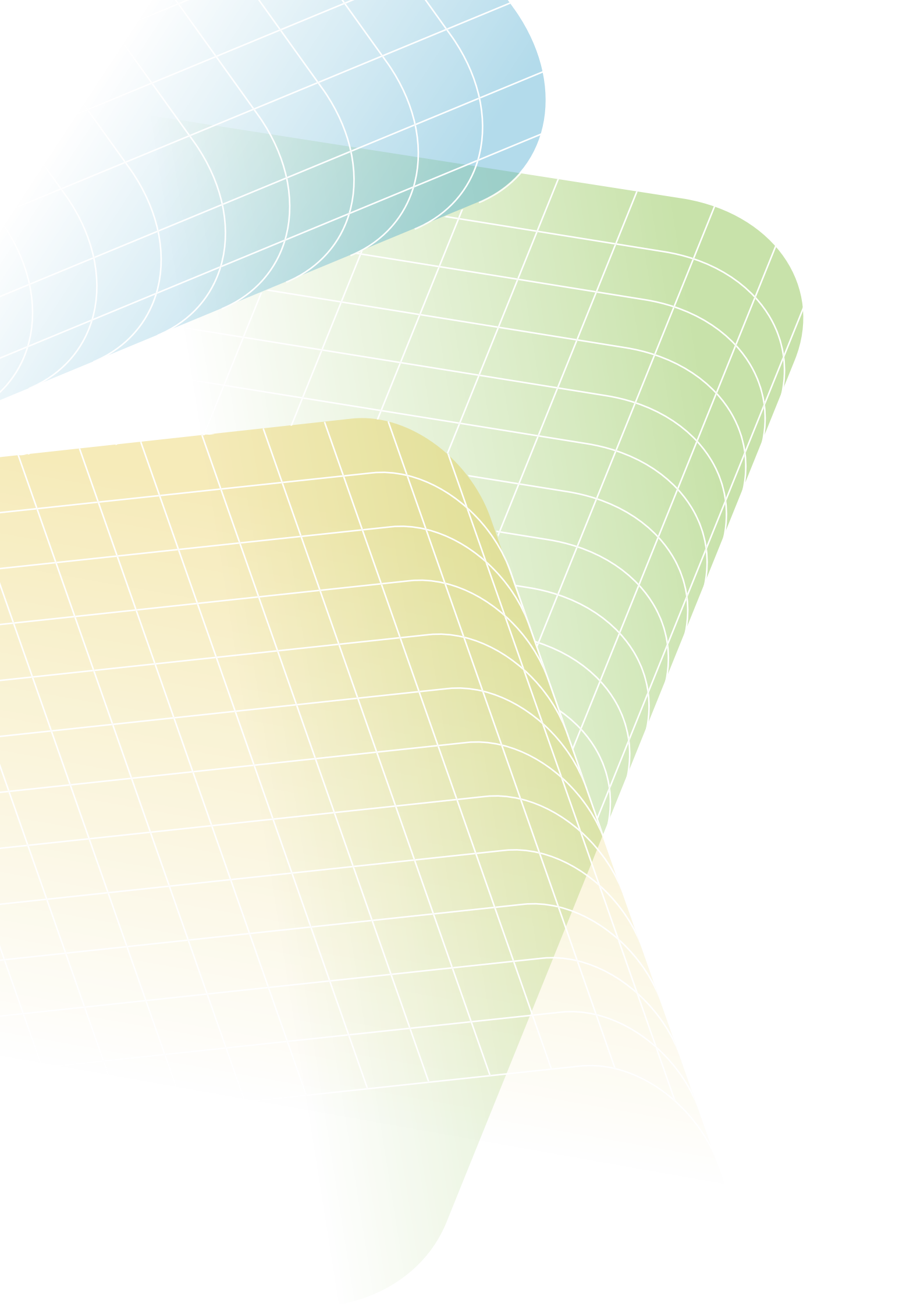

Annex: Further information on the work done by different groups on estimating investments in agricultural research

1. The Agricultural Science and Technology Indicators (ASTI) initiative

The ASTI initiative (www.asti.cgiar.org) evolved from the work that was carried out on agricultural research data indicators since the 1980s by two CGIAR centres, the International Service for National Agricultural Research (ISNAR) and the International Food Policy Research Institute (IFPRI). The International Service for National Agricultural Research ceased operations in 2004 and IFPRI was the sole facilitator of the ASTI initiative after that.

To carry out the ASTI national surveys, focal points are identified (normally from national agricultural research institutes), and three survey forms with different sets of questions are used for government and non-profit agencies; institutions of higher education; and the private sector. During the survey, time series data are collected for indicators related to research investments, research funding sources and research staff totals. Additional qualitative information is gathered during country visits through in-depth meetings with various agencies.

The surveys are quite detailed. For example, for government and non-profit agencies, spending is requested in three categories, namely salaries, operating and programme expenditures, and capital expenditures. The funding sources are categorized as follows: government core allocations; other government allocations; loans from multilateral donors; grants from bilateral donors, multilateral donors and private foundations; commodity levies and producer organizations; sale of goods and services; and other sources. The surveys also gather detailed information on the number of researchers working on specific commodities and in specific areas of research.

The focus of ASTI is on the national agricultural research systems, where "national" refers to domestically targeted research activities that are funded or executed by the research agencies within a particular country. This means that research activities undertaken by international and bilateral research agencies are excluded unless they are executed by national institutes. Research activities undertaken by short-term development projects are also excluded. The ASTI initiative defines agricultural research to include research on crops, livestock, forestry, fisheries, natural resources and the socioeconomic aspects of primary agricultural production. It also includes research concerning the on-farm storage and processing of agricultural products. Research and development in the agrochemical industry, agricultural machinery and the food processing industry off-farm is not included. Following the *Frascati Manual,* they do not include spending on activities such as science and technology information services

or on education and training, although research by PhD students at universities is included. The ASTI initiative also requests actual expenditure figures, not budgeted or projected expenditures.

The ASTI initiative groups' investments in agricultural R&D into four institutional categories (government, higher education, non-profit and private for-profit). Allocation is based on the "performer", i.e. the entity that carries out the research, not the funder of the research. For example, if a government institute receives research funding from the private sector, the institute is considered the performer and not the private sector entity. Categorization is sometimes difficult, but the *Frascati Manual* provides a decision tree to help. For example, for the Colombian Corporation for Agricultural Research and the National Institute for Agricultural Research in Uruguay, since their administrative control is non-governmental, but they continue to depend on the government for funding, the ASTI initiative categorizes their spending as government (ASTI, 2016).

2. USDA-ERS work on private sector investments

Over the last decade, economists at the USDA-ERS (www.ers.usda.gov) have made important contributions to estimates of both global private sector spending and public sector spending in high-income OECD countries. For the private sector, Fuglie *et al*. (2011, 2012) developed a dataset on agricultural R&D spending from 1994 to 2007 by leading firms worldwide, including those that are publicly traded and privately owned. Industry associations and private consulting firms specializing in agricultural input markets were contacted to identify leading firms conducting research in seven sectors of agricultural inputs and each firm's spending on agricultural R&D over time was then gathered. The seven agricultural input sectors included three for crops (i.e. seeds and biotechnology, pesticides and fertilizers), three for animals (genetics, health and nutrition) and the farm machinery sector. The animal sector included aquaculture.

Data were gathered using a number of different approaches. For research-intense sectors (such as seeds and biotechnology), they built a database of agriculture-related research spending by all firms in the sector with significant R&D expenditures. For large companies with several lines of business, they separated agriculture-related R&D spending from the other R&D expenditures. Data were gathered mainly from the firms' annual financial reports, supplemented by information from industry associations, consulting services and personal interviews with company representatives. For sectors where the private sector does less research (such as animal nutrition or farm machinery), many companies do not report their R&D spending. In these cases, they estimated the agricultural R&D spending as a proportion of the company's sales using the R&D intensity (i.e. R&D spending as a percentage of sales) that had been estimated for the given sector.

In addition to the seven agricultural input sectors, for comparison purposes, they also provided estimates of R&D spending in the food processing or food manufacturing industry. For this, they relied primarily on country-level estimates provided on the "food, beverages and tobacco" industry from the OECD ANBERD database. Countries covered in the database are OECD member countries and a selection of non-member economies. Fuglie *et al.* (2011) note that the data are limited and incomplete, but do not quantify how much data are missing. When compiling the country-level estimates, firms working in several different areas also tend to be

classified by their primary industry only. So, data on R&D from companies that engage in food manufacturing, but without it being the company's main business, would not be included.

Fuglie (2016) used the same approach as Fuglie *et al.* (2011) but expanded the work to include several new firms, as well as new data from India and China, and updated it to include data up until 2014. Like Fuglie *et al*. (2011), firms were classified into the same seven agricultural input sectors. Again, while noting that they have limited relevance for production agriculture, Fuglie (2016) gathered national data on spending by the food industry for comparison purposes, which were updated to 2012.

Following the approach of Fuglie *et al.* (2011), Fuglie (2016) defines private agricultural R&D as:

> **R&D by the business sector to develop new technologies for crop, livestock and aquaculture production. The business sector includes private and state-owned enterprises so long as they sell their products to the market. It excludes R&D by institutions financed by producer groups or industry associations as well as R&D by private universities.**

The role of state-owned companies is particularly important in China. For each of the seven sectors, industry associations and private consulting firms specializing on agricultural input markets were again contacted to identify the leading firms. As before, data on agricultural R&D expenditures were compiled from publicly available information, such as annual financial reports. When not available, data were gathered by contacting the individual firms directly or by estimating the R&D expenditure as a certain percentage of the company's sales.

3. USDA-ERS work on public sector investments in high-income countries

Heisey and Fuglie (2018a and, in a more detailed report, 2018b), describe the work they carried out at the USDA-ERS to build a comprehensive time series of public agricultural R&D spending for 31 high-income OECD countries. For 28 of the 31 countries, the series ran from 1960 to 2013 and for the other three it began in the mid-1980s or 1990s. For data after 1980, their main data source was the OECD Main Science and Technology Indicators database. Public R&D includes R&D covered by government (central/federal and provincial/state) and higher education institutions. In a limited number of cases, R&D by the private non-profit sector was also included – for many countries, these investments are small or not reported.

Like other research groups, they aimed to follow the principles and definitions laid out in the *Frascati Manual*. This classifies research expenditures in several ways and Heisey and Fuglie (2018a, 2018b) note that two classifications in the manual are most relevant to agricultural R&D. One is the "field of science" which includes a category on "agricultural and veterinary sciences" which has five subcategories: agriculture, forestry and fisheries; animal and dairy science; veterinary science; agricultural biotechnology; and other agricultural sciences. The other is the "socioeconomic objective" which contains a category on "agriculture" (covering all R&D aimed at promoting agriculture, forestry, fisheries and foodstuff production, or furthering knowledge on chemical fertilizers,

biocides, biological pest control, and the mechanization of agriculture, as well as concerning the impact of agricultural and forestry activities on the environment). Heisey and Fuglie (2018a, 2018b) indicate that their main interest is the "purpose" rather than the "content" of the R&D (the difference between them is illustrated nicely by Pardey *et al.* (2016a) who note that funding for a research project to improve the fuel efficiency of farm machinery could be placed under "agriculture" if classified by R&D purpose, but under "energy" if classified by R&D content). Heisey and Fuglie (2018a, 2018b) suggest that data categorized by the socioeconomic objective would therefore be more appropriate, as it more closely reflects the purpose of R&D. However, they note that in practice they had to rely more on the "field of science" because, *inter alia*, data on the socioeconomic objective were often missing (as also noted by Chartier *et al.*, 2015).

Heisey and Fuglie (2018b, Annex B) describe for each of the 31 countries the data that were available from different national and international databases for different years and different public sector R&D performers (governments, higher education institutions and private non-profit entities) and explain which data they decided to use, and why.

4. InSTePP

The International Science and Technology Practice and Policy (InSTePP, www.instepp.umn.edu) is a centre of the Department of Applied Economics of the University of Minnesota that engages in economic research on science and technology practice and policy, emphasizing the international implications. One of its areas of interest is the compilation and analysis of trends in global food and agricultural R&D expenditures. To enable this work, they have put together a database, including both public and private sector investments in food and agricultural R&D, amply documented by Pardey *et al*. (2016a). This version of the database from 2016 builds on earlier versions from 2009 and 2012.[12]

Like the other research groups working in this area, in building up the database they aim to follow the standards of the *Frascati Manual*. They also aim to report data on a "by performer" basis, so spending is assigned to the agencies that do the research rather than those that fund it. Additionally, they aim to compile data based on the "purpose" of research rather than its "content". When using databases from the OECD and other sources, they therefore seek to use the "socioeconomic objective" rather than the "field of science" classification, only using the latter when the former is not available.

For *public sector research expenditures*, they built a database consisting of 158 countries or territories spanning the period from 1960 to 2011. These included 37 high-income, 64 middle-income and 29 low-income countries or territories (they call them the 130 "core countries") plus 28 Eastern European and former Soviet Union countries.

For the 37 high-income countries, the most important data source for the period from 1990 to 2011 was the OECD databases, followed by national data. For the 93 low- and middle-income countries, Pardey *et al.* (2016a, Table 2) indicate that the main sources of data were ISNAR publications for older data, and ASTI in later years. For the 130 core countries, because of missing data,

12 www.instepp.umn.edu/instepp-international-innovation-accounts

almost 40 percent of the data points were estimated using the ARI-AgGDP approach for the time periods from 1990 to 1999 and 2000 to 2011 (Pardey *et al.*, 2016a, Table 3). For *private sector research expenditures*, they built a dataset to cover the 1980–2011 period. For the United States of America, primary data were collected and a purpose-built series using firm-level data was constructed. For 34 other high-income countries and territories, estimates drew heavily on OECD sources, particularly the ANBERD database. Here, they used four sectors (industries) in the ANBERD database that they considered to be relevant to food and agriculture, i.e. agriculture, hunting and forestry; food, beverages and tobacco; machinery; and chemical and pharmaceutical – see Pardey *et al.* (2016a), Tables 4 and 5. All of the R&D expenditures reported for the first two were deemed to be related to food and agriculture, and so they were included. For the third sector, 9 percent of the spending for the "machinery and equipment n.e.c (not elsewhere classified)" subsectors was considered to be related to food and agricultural R&D. For the fourth sector, they included 4 percent of the total spending on R&D in the "chemicals and chemical products" subsector as food and agricultural R&D. Percentages used for the last two sectors were derived from analysis of data from firms in the United States of America.

As previously noted (e.g. Fuglie *et al.*, 2011; Chartier *et al*., 2015), getting national private sector R&D data in high-income countries is a significant challenge. From Table 6 of Pardey *et al.* (2016a), it seems there are much missing data. For example, for the 2000 to 2011 period, about one-third of the data points were estimated using differing approaches, such as econometric methods, interpolation, or using a ratio of estimated private to public research spending.

For a small number of additional key countries, such as Brazil, Chile, China, India, Mexico, Türkiye and South Africa, they gathered the relevant national private sector data from local or international statistical agencies. They note that particular attention was paid to getting robust estimates from China. For the remaining low- and middle-income countries, they used an econometric model to get an estimate of the private sector research expenditure for each country, with the per capita GDP, public sector agricultural R&D investments and total R&D investments in the model.

Well-funded agricultural research and development (R&D) systems play an important role in transforming agrifood systems and helping countries to achieve the Sustainable Development Goals. The advantages of investing in agricultural R&D are also clear from looking at the past, where a wide range of studies have clearly demonstrated the substantial benefits that resulted from investments in agricultural R&D. The importance of investing in R&D has also been highlighted by governments on numerous occasions in intergovernmental settings. Gathering, compiling and analysing multi-year, multi-country datasets on investments in agricultural R&D are complicated tasks that require a lot of meticulous work and dedication. Only a small number of groups have worked actively in this specialized area. In some cases, they have used different procedures for gathering data on public and private sector investments in agricultural research. This report reviews the current situation and trends regarding investments in agricultural R&D in the world and presents some clear results emerge from recent studies.

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