Agricultural R&D investment intensity: A misleading conventional measure and a new intensity index

Alejandro Nin-Pratt

Environment and Production Technology Division, International Food Policy Research Institute (IFPRI), Washington, District of Columbia, USA

Correspondence
Alejandro Nin-Pratt, Environment and Production Technology Division, International Food Policy Research Institute (IFPRI), Washington, DC 20005–3915, USA. Email: a.ninpratt@cgiar.org

Abstract
The conventional wisdom that developing countries are significantly underinvesting in agricultural research and development (R&D) has been challenged by studies that found that the high rates of return in the literature result from data limitations and inadequate modeling choices. However, evidence of low research effort in developing countries as measured by the intensity ratio (IR)—the percentage of agricultural gross domestic product invested in agricultural R&D—has not been questioned. This article argues that the IR is an inadequate indicator of research effort and proposes an alternative index to measure R&D intensity. Using the proposed index, we find that the investment effort in developing countries is much higher than the one observed when the IR is used, that the contribution of low- and middle-income (LMI) countries to growth in global R&D intensity was higher to that of high-income (HI) countries in recent years, that the investment gap in LMI countries is close to 50% of R&D investment, and that the proposed development goal of a 1.0% value of the IR is beyond the possibilities of most Asian and African countries.

KEYWORDS
agriculture, development, investment gap, investment intensity, research, science technology

JEL CLASSIFICATION
O3, O1, Q1

1 | INTRODUCTION

It has become widely accepted among stakeholders in economic development that there is significant underinvestment in public agricultural research and development (R&D) in low- and middle-income (LMI) countries. This claim of R&D underinvestment is supported by a vast literature showing returns on R&D expenditure to be so high as to justify levels of investment at multiples of those found. (See, for example, Alston et al., 2000a, 2000b for an analysis and comparisons of results from this literature.) Evidence of agricultural R&D underinvestment also comes from available data on R&D investment intensity as measured by the intensity ratio (IR) in developing countries. This measure is often used as an indicator of the research effort made by a country and is defined as the percentage of agricultural gross domestic product (GDP) invested in agricultural R&D (excluding the for-profit private sector). For example, a weighted average (using agricultural GDP as weight) of IR values for the period 2001–2013 calculated using Agricultural Science and Technology Indicators (ASTI) data from 2018 shows an average IR of 3.2% for high-income (HI) countries including North America, Western Europe, Japan, Australia, and New Zealand;
1.1% for Latin America and Caribbean (LAC) countries, .5% for Sub-Saharan African (SSA) countries and only .4% for Asia–Pacific (APAC) countries.\(^1\) Estimated returns on R&D are expected to rise with distance from the technological frontier, reflecting the gains that follower countries can make from catching up (Griffith et al., 2004). Consequently, the observed low levels of research intensity reinforce the results from the rates-of-return literature, suggesting that returns on R&D investment should be truly large and that developing countries should increase R&D intensity in agriculture.

Many countries and areas use R&D intensity measures to monitor progress toward meeting development and policy objectives and, in some cases, to set explicit R&D investment targets. For example, governments at the Rio+20 conference (see Legget & Carter, 2012) agreed to develop a universally applicable set of sustainable development goals to promote coherent action on development with a strong focus on agriculture, food systems, and nutrition outcomes, areas linked to the goal of eradicating hunger and poverty. Among the targets defined under this general goal, there was a call for LMI countries to increase their agricultural R&D spending by a minimum of 5% annually over the next decade to reach an IR value of at least 1%. This widespread agreement on the need to promote agricultural R&D investment could have a significant impact on future allocation of scarce public resources in LMI countries, so it justifies a second look at the extent of the R&D underinvestment hypothesis, especially because this proposition rests on weak assumptions, mainly the high rates of return on agricultural R&D found in the literature and the low intensity of investment as measured by the IR.

With respect to the high rates of return on R&D argument, Alston et al. (1998) claim that the evidence in previous studies has been severely biased. They showed that when the effects of research on production are measured more appropriately, the estimated rate of return on research is closer to a normal market rate of return than to the very high rates that predominate in the literature. Alston et al. (2011) contend that many of the very large estimates of internal rates of return on aggregate R&D investments are simply implausible and, if taken literally, imply unbelievable impacts of agricultural research over lengthy time periods. They state that these high rates result from data limitations and from model choices that require the imposition of restrictive assumptions, not from theory, but from data constraints. Consequently, they claim that the very high rates of return found in the literature might have damaged the case for public support of R&D.

If rates of return on agricultural R&D appear not to be as high as they were assumed to be in the past, how does this finding relate to the low research intensities observed in developing countries as measured by the IR? Is R&D investment in developing countries as low as this indicator seems to show? This article is concerned with the meaning and measurement of IR at the country level as an indicator of research intensity and its use to define policy targets or conduct cross-country comparisons. First, it will look at the correlation between IR and a series of structural variables to determine the extent to which IR depends on country characteristics not controlled by policymakers, thereby making it an inadequate indicator to compare different countries’ research efforts. Second, it will develop an index of R&D intensity to (i) unequivocally rank and compare countries according to R&D intensity levels, (ii) identify underinvesting countries by comparing countries with similar characteristics, and (iii) use this information to determine intensity gaps and tentatively quantify R&D investment needs for different countries and regions.

This study makes two main contributions to the literature. First, it looks back at the seminal articles by Alston et al. (1998, 2011) to resume the discussion on the evidence of underinvestment in public agricultural R&D in LMI countries. Recent studies have focused on some of the specific aspects behind the high estimates of rates of returns to R&D mentioned by those articles. For example, a few studies have introduced improved econometric methods to capture the lagged effects of R&D investment instead of defining models and lags based on data constraints and empirical reasons, one of the reasons for inaccurate estimations of rates of return. An example of this literature is the article by Baldos and colleagues (2019) who use Bayesian inference to statistically estimate the underlying parameters of the R&D lag weight structure and knowledge stocks from observed data on agricultural productivity and R&D expenditures for the United States. Fuglie (2018) adopts the framework developed by Alston et al. (2010) that uses a gamma distribution and R&D capital lifespan of up to 50 years to capture the technology maturation and the obsolescence during this lifespan in world agriculture. To our knowledge, no study has discussed the low R&D investment intensity observed in many LMI countries, an indicator still being used as evidence of underinvestment in public agricultural R&D.

This study also contributes to the literature on policy analysis looking at scenarios of increased R&D investment analysis to set explicit R&D investment targets. For example, Kristkova et al. (2017) analyze the impact of public agricultural R&D investments on agricultural productivity and long-term food security to derive policy recommendations, concluding that doubling the R&D intensity would

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\(^1\) Australia, Japan, and New Zealand, although part of APAC, are not included as they are included in the group of HI countries.
soften the land constraints and substantially decelerate food prices. Mason-D’Croz et al. (2019) use the IMPACT framework of linked biophysical and structural economic models to examine developments in global agricultural production systems, climate change, and food security. They conclude that investments to increase agricultural productivity can offset the adverse impacts of climate change and help reduce the share of people at risk of hunger in 2030. In a recent article, Baldos and colleagues (2020) also use gamma distributions with 35- and 50-year lags for developing and developing countries, respectively, to analyze the research cost of adapting agriculture to climate change. This literature can benefit from a better understanding of the constraints faced by countries when setting R&D investment scenarios.

The rest of the article is organized as follows. The next section looks at the IR and its relationship with structural country characteristics and discusses why this is an inadequate measure of countries’ investment efforts. Section 3 presents the methodology and approach used to propose a new index that controls for these structural characteristics and is a more reliable measure of R&D intensity. Section 4 presents results and country comparisons and quantifies the intensity gap using the proposed index. Section 5 concludes the article.

2 | THE INTENSITY RATIO AND COUNTRY COMPARISONS

A simple comparison of average IR values of 10 selected countries for the period 2001–2013 (Figure 1) is enough to show some of the difficulties that arise when using the IR to measure R&D investment intensity. If the IR is a good measure to compare research intensity between countries, Figure 1 shows that HI countries like Japan and the United States make a much higher effort in agriculture R&D investment than most developing countries, which is normally expected. But take, for example, the cases of China, India, and Brazil. These countries show IR values that are only a fraction of those of Botswana, with Brazil’s IR almost four times larger than China’s, and India’s research effort only 60% of that of China. Why do Brazil, China, and India differ so greatly, and why are their IR values smaller than Botswana’s when it is well established that the three aforementioned countries are leading agricultural research middle-income countries with comparably large, relatively developed, and successful R&D systems (Beintema et al., 2006; Fan, 2000; Fan et al., 2006; Pal, 2008; Pal & Byerlee, 2006)?

This article argues that the IR is an inadequate indicator to measure and compare the research efforts of a diverse group of countries, which makes the comparison in Figure 1 a misleading exercise. The reasons for the inadequacy of the IR as a measure of R&D investment effort can be found in the more general literature on R&D investment at the firm level. This literature shows that poor countries invest far less in R&D as a share of their GDP than rich countries. One explanation for this fact, relevant for this analysis, is that the necessary complementarities to R&D expenditure are likely to diminish in low-income countries and hence reduce the efficacy of a given unit of R&D. In other words, the efficacy of R&D investment in developing countries is much lower than in HI countries owing to any number of institutional and educational factors that

![Intensity Ratio for selected countries, average values 2001–2013](image-url)

**Figure 1** Intensity Ratio for selected countries, average values 2001–2013

*Note: The Intensity Ratio is defined as IR = (agricultural R&D spending)/AgGDP*
can offset the Schumpeter catch-up effect and significantly reduce the returns on R&D (Goñi & Maloney, 2014).

Lederman and Maloney (2003) looked at the links between development and R&D investment and found that R&D rises exponentially with the level of development as measured by GDP per capita, mainly because HI countries tend to have higher government capacity to mobilize public R&D expenditures and often have higher-quality research institutions. Richer countries also have better intellectual property protection and deeper credit markets, which support private R&D. Other authors have emphasized the importance of market size as a determinant of innovative activity. For example, Eaton et al. (1998) found that Europe’s research intensity was lower than that of the United States because Europe has smaller and more fragmented markets for innovations than the United States. Notably, in this case, market size is related to the absolute value of R&D investment, not to the IR. As will be discussed below, the actual size of the economy could be negatively related to the IR.

A first conclusion derived from the literature on R&D investment is that richer economies are expected to show higher IR values. If this conclusion also applies to R&D in agriculture, it could be at least a partial explanation of observed heterogeneity in IR between countries. At the sectoral level, other factors may affect IR. In the case of agriculture, one of these factors is the size of the agricultural sector relative to the economy. A country with a small share of agriculture in GDP could potentially allocate relatively large amounts of resources to agricultural R&D investment, given that the investment needed is small relative to the size of the country’s economy and the overall resources available. This could help explain why, in general, IR is higher in HI countries than in LMI countries, since the share of agriculture in GDP decreases with income growth. This explanation could also apply to developing countries with small agricultural sectors relative to GDP, as in the case of Botswana, shown in Figure 1.

As in the more general literature on R&D, the size of the economy should be another factor affecting agricultural R&D investment and IR. A large economy could facilitate the development of innovation activities in agriculture because it would have a larger market for innovations in agriculture and in other sectors. However, the effect of a large economy does not necessarily result in higher IR levels. Economies with large markets for innovation might depend less on investment from the public sector and nonprofit organizations, which might result in less R&D investment relative to agricultural GDP (AgGDP). However, this relationship could also be affected by other variables like income per capita, spill-ins, and the relative size of agriculture, making it difficult to determine a priori the degree of its effect on IR.

A country’s potential to benefit from spillovers from other countries (spill-ins) is another factor that could affect IR. For example, countries with similar output compositions (reflecting similar agroecologies and natural resources) and similar use of capital and land per worker in agriculture are “closer” to each other than to countries in different agroecologies and with different relative factor prices (for example, land- and capital-abundant countries compared with land-scarce and labor-abundant countries). Countries with high potential of receiving spill-ins from other countries could show lower IRs from R&D investment. The negative correlation between spill-ins and IR could be expected if there is a simple linear relationship between these variables. However, this relationship could be more complex because countries might need to invest in R&D to take advantage of spill-ins, and the level of investment needed could vary along the distribution of IRs.

Section S1 in the Supporting Information Appendix shows the results of different measures of correlation between the IR and the four main factors, according to the literature, assumed to affect its value: (i) income, (ii) size of the economy, (iii) size of the agricultural sector, and (iv) potential to receive spill-ins. The results show that the IR is highly correlated to these structural variables that policymakers do not control. The effect of these variables on IR is not linear but changes with the level and combination of the four variables. For the IR to be a good measure of R&D investment intensity, one must compare countries with at least similar levels of income, size of the agricultural sector, size of the economy, and potential to receive spill-ins. In other words, countries invest differently in R&D relative to the size of their agricultural sector because of their structural differences. Those differences are precisely what make IR an unreliable indicator of a country’s effort in R&D investment.

Owing to the limitations of the traditional IR as an indicator of R&D intensity and as a tool to compare and rank countries according to their R&D investment efforts, this article proposes a multifactor indicator of R&D intensity that combines four different partial intensity ratios of R&D investment with AgGDP, GDP, income, and potential spill-ins. By controlling for the different structural variables that determine R&D investment efforts, the resulting meaningful comparisons of R&D intensity will look at the efforts of countries with similar structural characteristics.

The procedure used to calculate this index is akin to the one followed to build any multifactor index, such as a price, output, or input index. The actual maximum R&D intensity that a country can achieve will depend on the mix of partial measures of its R&D intensity. Countries with the
same mix of the four partial intensity ratios are expected to show similar values of the composite intensity index. Differences in the index between countries with similar values of the partial intensity components of the index will indicate higher R&D intensity by the country with higher composite index.

There are two major difficulties in building this index. The first problem is to define the weights necessary to aggregate the individual indicators into a single measure of R&D intensity. These weights should reflect the importance that the five determinants of R&D have as constraints of R&D investment in each country. For example, R&D investment in a small, HI economy could be constrained by the relative size of GDP, by a small agricultural sector, or both, but it is less likely for income to be a major constraint. Therefore, GDP and AgGDP should enter the intensity index with a higher weight than income to reflect the importance of these constraints on R&D intensity. The second problem is to be able to compare similar countries in terms of the importance of the four partial intensity measures in the composite index. To obtain a conceptually meaningful definition of an intensity index as the one discussed here, one must overcome these two difficulties. The intuition of the approach followed to build the index is presented and discussed in the Section 3. Technical details of the proposed methodology are included in Sections S2 and S3 of the Supporting Information Appendix.

3 | APPROACH AND DATA

The data envelopment analysis (DEA) approach is used to obtain a multifactored R&D intensity measure, which is called the Agricultural R&D intensity index (AII). This index calculates the R&D investment of a country relative to the main structural factors affecting intensity: the size of the economy (proxied by GDP), the size of the agricultural sector (proxied by AgGDP), income (proxied by GDP per capita), and potential spillovers (proxied for a country as the sum of R&D investment of all other countries weighted by a measure of the similarity of country i’s output and input composition with output and input composition of other countries).

In generic form, the multifactored R&D intensity measure can be represented as:

$$\text{AII}_i = f\left[ \frac{(R&D_i/GDP_i)}{(R&D_1/AgGDP_1)} \times \frac{(R&D_i/y_i)}{(R&D_1/SP_j)} \right],$$

where $\text{AII}_i$ is the AII of country $i$, $R&D$ is expenditure on R&D and $GDP$, and $y$ is income per capita, $SP$ measures potential spillovers, and $f[\cdot]$ is a function aggregating the four partial intensity measures into a single number that measures the R&D investment intensity of country $i$. This problem is equivalent to that of estimating an index of quantities when no prices are available, where the main difficulty is to determine the weights to be used to aggregate the partial intensity measures.

A well-known feature of DEA is that it looks for endogenous weights that maximize the overall score for each decision-making unit given a set of other observations, yielding the most favorable country-specific weights. The DEA approach has been used extensively to solve this problem in production analysis when prices of inputs or outputs are not available, and it has been extended more recently to build indexes that comply with characteristics required by index theory. The approach used by Whittaker and colleagues (2015) is adapted here to build a multifactored measure of R&D intensity.

How are the weights that aggregate the different factors obtained? The best way to understand this is to introduce the ratio form of the DEA problem.

$$\max_v \Gamma_i = \frac{Y_i}{\sum_{h=1}^{N} u_{i,n} z_{i,n}}$$

$$s.t. \frac{Y_j}{\sum_{n=1}^{N} u_{j,n} z_{j,n}} \text{ with } j = 1, \ldots, K$$

$$v \geq 0.$$  

The optimal solution of this problem gives values of $v$ that maximize the ratio $\Gamma_i$, for country $i$, subject to the constraint that ratios of all countries $(j = 1, \ldots, K)$ are equal or greater than 1. Adapting (1) to the problem at hand in this article, we can think of $Y_i$ as the level of R&D investment of country $i$, and the $z_{i,n}$ as the factors affecting the level of intensity measures in the composite index. To obtain a conceptually meaningful definition of an intensity index as the one discussed here, one must overcome these two difficulties. The intuition of the approach followed to build the index is presented and discussed in the Section 3. Technical details of the proposed methodology are included in Sections S2 and S3 of the Supporting Information Appendix.

2 Notice that the four factors chosen are based on the literature on private R&D and the discussion in Section 2. These four variables are proxies for structural variables that constraint policymakers’ decisions on R&D. Other variables like population, specialization in agriculture, education, and road infrastructure among others were also considered but were discarded for two main reasons: (i) the selected variables provided the best fit of the quantile regressions used to model conditional quantiles of the joint distribution of IR (Section S1 in the Supporting Information Appendix); (ii) calculating the AII including more variables in the index didn’t change significantly the values of the AII, nor the rankings of countries that result from those values.
The intensity ratios are expressed as the inverse of R&D spending / AgGDP and R&D/income, to represent the analysis as an input-oriented problem, where A, B, and C determine the unit isoquant, showing the value of AgGDP and income per unit of R&D invested. AgGDP = agricultural gross domestic product; AII = Agricultural R&D intensity index; R&D = research and development.

In other words, problem (1) finds the value of the weights ($v_{i,n}$) that can be used to aggregate the $n$ factors so as to maximize the R&D intensity ratio $\Gamma_i$. We obtain the $v_{i,n}$ weights for all $K$ countries by running problem (1) $K$ times. This is not exactly the problem solved to calculate the AII index, but it shows the intuition on how to obtain the weights used to calculate the index. The actual problem solved is a variation of (1) using the inverse of ratios $Y/z_n$ and solving a minimization instead of the maximization problem in (1).

The example in Figure 2 demonstrates how to calculate the index comparing countries with the same proportion of the $N$ factors. The axes in the figure represent values of R&D investment relative to two variables, income (GDP per capita) and AgGDP. The use of two inputs ($N = 2$) in the figure is only for illustrative purposes. A formal analysis showing the actual LP problem used extended to $n$ variables can be found in Sections S2 and S3 of the Supporting Information Appendix. In Figure 2, each point represents a country with coordinates AgGDP/R&D and income/R&D, in the vertical and horizontal axes, respectively. Notice that these coordinates represent the inverse of partial intensity ratios, with the measure in the vertical axis being the inverse of the IR normally used to measure the intensity of agricultural R&D investment. The farther a country is from the origin, the lower its R&D intensity.

How do we compare intensity in this setting? For example, in the case of country $D$, a valid comparison to determine R&D intensity is to compare it with point $D^*$, a linear combination of countries $A$ and $B$. This is because $D$ and $D^*$ have the same proportion of AgGDP and income (they are in the same ray through the origin). In this case, $D^*$ shows much higher values of R&D/AgGDP and R&D/income than $D$, which means that the R&D intensity of point $D^*$ is higher than that of $D$. Countries $A$, $B$, and $C$ in Figure 2 are the countries with highest R&D intensity because there is no other country closer to the origin along the respective rays through the origin and these three countries (rays $OA$, $OB$, and $OC$ in Figure 2, respectively).

Investments by countries $A$, $B$, and $C$ outline the “intensity frontier.” This frontier defines the space of investment intensity for the sample of countries, with the highest intensity defined by points $A$, $B$, and $C$, and by all linear combinations of these three points (the lines connecting $A$, $B$, and $C$). Countries with less intensive investment are in the space above and to the right of the frontier. The DEA approach uses the piecewise linear frontier as the benchmark curve and measures distances.
of country vectors relative to this frontier. The distance of each country from the frontier is calculated as the proportional reduction of AgGDP and income needed to bring each point in the “intensity space” to the frontier. For example, the intensity measure for country D can be calculated as $AII_D = OD^*/OD$, which is the distance of country D to the frontier. The result of multiplying the AgGDP and income of country D by $OD^*/OD$ is the coordinates of point $D^*$, that is, the value of AgGDP and income of vector $D^*$, the point on the frontier with the same proportion of AgGDP and income as country D. In this way, the multifactored intensity measure for country D ($AII_D$) is calculated as the distance between D and a similar point at the frontier. This distance is a measure of the difference of investment intensity between D and the maximum potential investment (investment at the frontier). Countries at the frontier also have, by definition, intensity index values equal to 1 because the distance of each of these countries from the frontier is $AII_A = OA/OA = AII_B = OB/OB = AII_C = OC/OC = 1$. Countries in the intensity space above the frontier will show AII values between 0 and 1. Comparing frontier countries with country D in Figure 2 establishes the intensity indexes $AII_A = AII_B = AII_C = 1 \geq AII_D \geq 0$. The closer the AII is to 1, the higher the investment intensity of that country—that is, the higher R&D investment relative to the value of AgGDP and income.

The discussion on the intuition of the methodology used here shows that the DEA approach allows us to determine the maximum potential intensity that a country can reach (given observed intensities of all countries). As a corollary of this, it allows us to obtain the actual intensity gap for that country, which can be measured as the difference between maximum potential intensity and actual intensity. This method also allows us to express the potential intensity for each country in terms of any of the partial intensity ratios of the AII. For example, as discussed above, the coordinates of the efficient point $D^*$ are $Y_D^* = Y_D \times (OD^*/OD) = (AgGDP/R&D)_D \times (OD^*/OD)$ and $X_D^* = X_D \times (OD^*/OD) = (income/R&D)_D \times (OD^*/OD)$. From these expressions, we obtain the potential IR for country D as $IRP_D = 1 / [(AgGDP/R&D)_D \times (OD^*/OD)]$, as one of the coordinates of the reference point for D at the intensity frontier.

4 | RESULTS

Figure 3 plots the average shadow shares in four developing regions—Asia-Pacific (APAC), Central and West Asia, and North Africa (CWANA), Latin America and the Caribbean (LAC), and sub-Saharan Africa (SSA)—and in high-income (HI) countries. The size of the agricultural sector (measured by AgGDP) shows the largest contribution to the AII in all regions except APAC, followed by GDP which has its largest value among APAC countries. The contribution of income and spill-ins to the index is smaller than that of AgGDP and GDP in all regions except APAC. This region shows the highest weight for GDP, the highest contribution of income and spill-ins, and the lowest contribution of AgGDP among all regions. In contrast to the case of APAC, SSA, and LAC show the highest contribution of AgGDP to the AII and the lowest contribution of GDP.
and spill-ins among LMI regions. Weights for CWANA and HI countries show values between those of APAC and LAC. The weight of income is highest for SSA and APAC (.15 and .14, respectively) and contributes with the smallest weight to all other regions.

The average values of the shadow weights obtained for the different regions help to explain why IR values for China and India shown in Figure 1 are so low compared to other countries, as economic size and income play major roles in determining R&D intensity. This should be the case not only for Asia, but for other LMI countries with similar proportions of AgGDP, GDP, income, and spill-ins to those of Asian countries.

Figure 4 compares the proposed AII with the conventional IR measure for LMI countries using the United States values of AII and IR as reference to facilitate comparisons (United States coordinates in the figure are [1, 1]). The AII and IR are shown as the coordinates of the country points in the vertical and horizontal axes, respectively. The 45° line shows the points where the two measures take the same value as a proportion of United States values. The correlation between the two indicators in Figure 4 is .68 (recall that IR is one of the components of AII), but the two measures result in very different country rankings of R&D intensity.

If we use the IR as the measure of R&D investment intensity (along the horizontal axis in Figure 4) we find that Botswana, is the country with the highest investment intensity, even higher than that of the United States, which is close to that of South Africa and followed by Namibia and Brazil. Asian countries like China and India perform very poorly in terms of intensity measured by IR, with values that are between 10% and 25% of those of the United States.

The AII, measured along the vertical axis, presents a very different picture of R&D investment efforts. Here, investment efforts by China and Brazil are higher than those of the United States. These three countries show the highest investment intensity, much higher than that of Botswana, Namibia, and South Africa, countries with the highest IR values of the sample countries (where the intensity of these countries is 60–70% of that of the United States). Most countries above the 45° line (countries for which IR shows lower investment intensity than the AII) are in Asia, including Iran, China, India, Malaysia, Indonesia, Bangladesh, Pakistan, and Vietnam. Other countries above the 45° line are Kenya, Nigeria, Uganda, and Ethiopia from SSA; Brazil and Argentina from LAC; and Egypt from CWANA. The difference in the shadow weights between Asian countries and other regions shown in Figure 2 is likely related to the high proportion of Asian countries above the 45° line, especially for the importance of the size of the economy, spill-ins, and income compared to countries in other regions (higher weight for these three variables in the AII). The importance of income also could be playing a role in the higher intensity shown by SSA countries like Ethiopia and Nigeria.
From here, it is worth examining the trends of R&D intensity using the AII and comparing them with IR trends to see if these indicators present different conclusions when measuring the world’s effort in agricultural R&D investment. Figure 5 shows the evolution of weighted averages of the AII and IR for LMI and HI countries measured relative to the values of the United States in 2011. As in the case of individual countries in Figure 4, the AII gives a different picture of intensity levels and regional trends. The AII in HI countries only increased between 2001 and 2009 falling after that year to reach a value of .78 in 2013, below its level in 1981. AII in LMI countries increased from about .60 in the mid 1990s to .78 in 2013, the same AII value of HI countries in that year. These changes represent an increase in R&D investment intensity of 30% in LMI. In contrast with the AII results, the IR shows no significant changes in LMI countries (from .20 in 1981 to .22 in 2013), while in HI countries the IR more than doubled between 1981 and 2009 (from .72 to 1.62), falling after that year to reach a value of 1.22 in 2013. Trends of the AII and IR for different LMI regions and the aggregated HI region can be found in Section S4 of the Supporting Information Appendix.

A useful feature of the method used to calculate the AII index is that it can measure the R&D intensity gap of a country by comparing the multifactored intensity of this country with that of countries showing the highest intensity and a similar mix of the four ratios with the analyzed country. Countries showing the highest intensity for different combinations of the individual intensity indicators are the countries that define the “intensity frontier.”

Figure 6 highlights the investment efforts made by LMI countries, showing the evolution of the investment gap between 1981 and 2013, defined as the difference between the potential R&D investment and the actual investment and measured as a percentage of R&D investment. In relative terms, the gap decreased from 104% to 50% of R&D investment between 1981 and 2013, with peaks of 120% and 130% in 1983 and 1994, respectively. Figure 6 also shows the evolution of the value of the intensity gap for LMI countries, measured in billions of 2011 PPP dollars. The investment needed to close the gap (on top of actual investment) increased until 1994 when it reached $17 billion. It decreased to $10 billion in 1998 and in 2004, and showed a growing trend after that year, reaching $14 billion in 2013; when compared with total R&D investment by LMI countries of $27 billion in that same year, it reveals the 50% gap shown by the dotted line in Figure 6.

It is important to keep in mind that the goal for each country should not be to close its R&D gap. The AII and the investment gap are simply investment intensity indicators to compare R&D investment efforts across countries. As such, they should be used to identifying countries that

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3 Agricultural gross domestic product is used as a weight to calculate regional averages, so results should be driven by countries like the United States, Japan, China, India, Brazil, Indonesia, and Nigeria, among other large economies within each region.
are likely to be underinvesting and to get a rough estimate of the size of that underinvestment and derive implications to evaluate different investment targets. For example, given the results obtained with the AII, what are the implications of trying to achieve the 1% IR as the target of R&D efforts as proposed by the sustainable development goals? To analyze this, we use the fact that the methodology employed to calculate the intensity gap for a country measures the proportional contraction of the four partial intensity factors that is needed to reach the same level of intensity than the country with the same proportion of the partial factors and the highest intensity (see Figure 2). We thus can express the intensity gap in terms of any of the four partial intensity factors by applying the proportional contraction obtained for the AII to any of the partial intensity factors. Applying this proportional change to the actual IR indicates the potential IR for every country.

Figure 7 presents the average 2011–2013 IR of selected LMI countries in different regions, together with the potential IR calculated using the AII, to measure the distance to the maximum observed IR for a country with similar characteristics. The 1% target for the IR seems to be relevant for two of 10 APAC countries. All except three countries in SSA show potential IRs greater than 1.0. What are the implications of using the 1% target to calculate the investment gap as proposed by the sustainable development goals instead of using the AII? If we consider all LMI countries (Table S3 in the Supporting Information Appendix), with a 1% IR target, the calculated gap for the sample countries becomes $26.2 billion 2011 PPP dollars, two times larger than the gap calculated using the AII (12.8 billion 2011 PPP dollars). This means that R&D investment will need to increase by 100% to close the gap, compared to 50% as calculated with the AII.

Based on these findings, the 1.0% target for the IR would demand an enormous investment effort for APAC countries and for most of SSA countries, and in most cases, it is not feasible at present levels of income and relative sizes of the economy and the agricultural sector in these countries. That said, the 1.0% IR has already been achieved by SSA countries like South Africa, Namibia, Botswana, and Zimbabwe and by LAC countries like Argentina, Brazil, Chile, Costa Rica, Mexico, and Uruguay. However, and except for Brazil, these countries are still below their potential IR as estimated here.

5 | CONCLUSIONS

This article argues that the IR is an inadequate indicator to measure and compare agricultural research effort at the country level. This is because this measure assumes that the level of R&D investment in every country should be proportional to the size of its agricultural sector. The literature on R&D investment and the analysis conducted in this article show that the capacity of countries to invest does not depend only on the size of their agricultural sector.
sector but also on other structural variables not controlled by policymakers. To overcome the problems of the conventional measure of R&D intensity, this article proposes a multifactored indicator of R&D intensity that combines four different intensity ratios, each relating R&D investment to one of four variables that are proxies for structural characteristics that affect a country’s possibilities for investment. These variables are AgGDP, representing size of the agricultural sector; GDP as a proxy for the size of the economy; GDP per capita as a measure of income; and an indicator of potential spill-ins that measures the distance between countries based on similarities in their mix of outputs and inputs used in agricultural production. The main difficulty in building this indicator is to define the weights to use to aggregate the five partial intensity measures into a single index of intensity. These weights should reflect the importance that each of the five individual ratios included in the index has as a constraint on investment in each country. It solves the problem of defining these weights by using a DEA approach. This method is ideally suited for the task at hand because it yields the most favorable country-specific weights for the different components of the proposed intensity measure. From these results, the AII provides a far different picture of international agricultural R&D investment intensity than the one obtained using the conventional IR. When using the IR as a measure research intensity indicator, HI countries show the highest levels of R&D intensity and seem to have been driving the R&D investment efforts in the past 30 years, significantly increasing the IR. In contrast, when using the AII as the measure of investment intensity, the results indicate that several LMI countries like Brazil, China, Kenya, and India have all made large investment efforts comparable to those found in the United States and that LMI countries have increased investment intensity at similar rates and to similar levels than HI countries. As a result of these efforts, the investment gap in LMI countries decreased from 104% to 50% of investment between 1981 and 2013, a reduction explained by increased investment in all LMI regions. To close the R&D intensity gap in developing countries as measured by the AII, countries will need to invest $13 billion more than the $26 billion (US dollars, 2011 PPP) invested on average in 2011–2013, an increase of 50% of total actual R&D investment.

Finally, when using the IR as a measure of R&D intensity and the 1% target for LMI countries as defined in the sustainable development goals, the calculated investment gap is twice the size of the one obtained using the AII. According to our results, using the proposed 1% target will result in the misallocation of scarce public funds in LMI countries.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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