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The Role of Research and Development in Shaping Agricultural Labor and Land Productivity in Colombia: 1981-2016

Juan P. Taramuel, Wanki Moon, Scott D Gilbert, and C. Matthew Rendleman

Colombia appears to be aligned with the normal path of economic transformation given that the share of agriculture has decreased and the non-agricultural sector has become dominant in the economy. In the process, the agricultural sector was expected to increase its productivity. However, Colombian agricultural productivity growth has been slow and has lagged compared with other Latin American countries. This paper employs cointegration and vector error correction (VEC) models to analyze the impact of agricultural research and development spending and other factors on agricultural output, labor, and land productivity in Colombia for the period 1981-2016. The Johansen cointegration test suggests that there is a long-run relationship between R&D spending and agricultural output and land productivity in Colombia. The downward trend in R&D spending observed in recent years in Colombia should be reversed to promote agricultural and economic development through improvements in agricultural productivity.

Key words: Agricultural R&D, Colombia, Partial Factor Productivity

The economic growth theory proposed by Rostow-Kuznets indicates that as an economy grows, the shares of the agricultural and industrial sectors decline, and it moves toward a service-based economy (Shaffer, Deller, and Marcouiller, 2004). At first glance, Colombia has been following the normal path of economic transformation. As shown in Figure 1, the service sector has become an even more dominant sector in the Colombian economy with its contribution to GDP increasing from 45.2% in 1965 to 59.1% in 2010 (Clavijo, Vera, and Fandiño, 2013). The manufacturing sector dropped from 21.1% to 14.2% and the agricultural sector from 27.8% to 8.1%. However, research suggests that the structural transformation has not been very healthy in Colombia. For example, Clavijo et al. (2013) show that Colombia has exhibited a premature deindustrialization due to the energy-mining boom since the late 1970s. Further, agricultural productivity growth in Colombia's agriculture has been low relative to other Latin American and Caribbean (LAC) countries including the Andean states (Ludena, 2010; Nin Pratt et. al., 2015; Pfeiffer, 2003). These characteristics of Colombian economic growth diverge from the Rostow-Kuznets economic growth theory which expects that agricultural productivity grows as its share declines.

The poor agricultural performance in Colombia has been associated with the following factors: (i) the lack of formality and security of land tenure in Colombia, which has led not only to

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expansion of illegal crops, but also to high levels of land concentration (Berry, 1995; Muñoz-Mora, Tobón, and D'Anjou, 2018; Organisation for Economic Co-operation and Development (OECD), 2015); (ii) inadequate agricultural infrastructure (Bravo-Ortega and Lederman, 2004; Lozano-Espitia and Restrepo-Salazar, 2016); (iii) political instability, armed conflict, inappropriate trade policy, and macroeconomic mismanagement (Jiménez, Abbott, and Foster, 2018). In addition to them, typically in developing countries, lack of investment in research and development (R&D) in agriculture represents a major impediment to agricultural development. Researchers have shown that R&D plays an important role in determining agricultural productivity in the short- and long-run in many countries across the world (Färe, Grosskopf, and Margaritis, 2008; Khan et al., 2017; Makki, Tweeten, and Thraen, 1999). While there are studies analyzing the role of R&D expenditures at the regional level in Latin America (Alston et al., 2010; Echeverría, 1998; Stads and Beintema, 2009), few studies have focused specifically on Colombian agriculture (Beintema, Romano, and Pardey, 2000; Junguito, Perfetti, and Becerra, 2014).

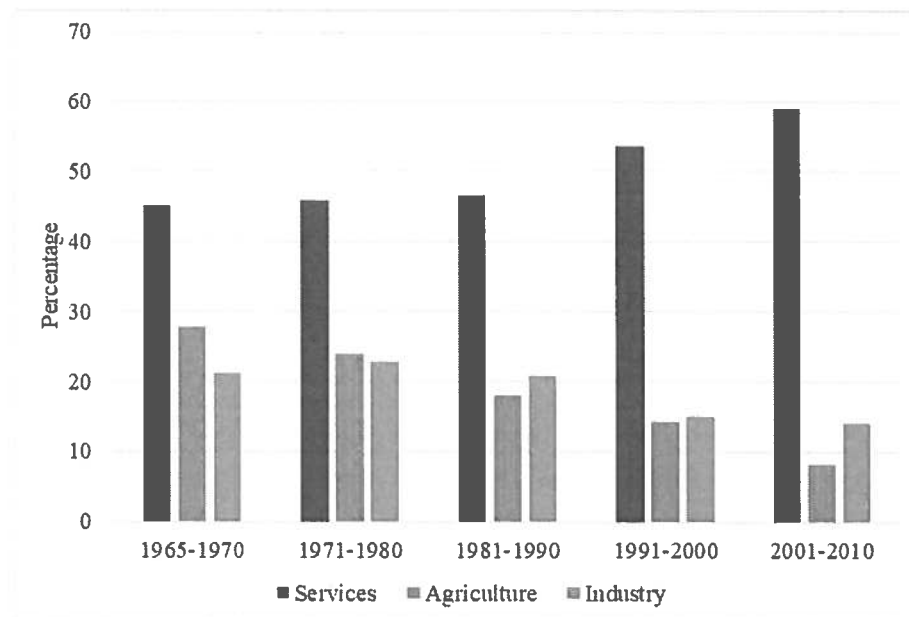


Figure 1. GDP by sector in Colombia, 1965-2010.

Source: Clavijo et al. (2013).

The primary purpose of this paper is to shed light on the impact of public R&D spending on agricultural growth and partial factor productivity (PFP) in Colombia. In particular, this paper aims to estimate the long-term relationship between R&D expenditures and agricultural productivity growth in Colombia. In consideration of the time-series properties of our data including agricultural output and productivity growth and R&D expenditures between 1981 and 2016, we conduct tests for stationarity of variables and use cointegration models. The rest of the paper is organized as follows. Section 2 presents a literature review illustrating the role of agriculture in economic development, determinants of agricultural productivity/output, agricultural productivity, and R&D

spending trends in Colombia. Section 3 presents data for the variables used in this study and their trend over time. Section 4 presents empirical models and estimation results. Section 5 highlights the role of the state in improving agricultural productivity in Colombia.

Agricultural Growth, Productivity, and R&D Spending

The early literature in economic development relegated agriculture to a mere provider of surplus labor to the urban manufacturing sector (Lewis, 1954). Yet, Johnston and Mellor (1961) showed that agricultural growth is important for economic development in consideration of the following critically important five roles it performs: (i) ensuring food supply; (ii) releasing labor; (iii) expanding market for industrial production; (iv) increasing supply of domestic savings; and (v) providing foreign exchange. Agricultural growth may come from using more inputs (e.g., land) or from improving productivity. Researchers highlight the importance of the latter as a way of achieving overall economic development along with agricultural growth and poverty reduction (Ivanic and Martin, 2018; Ruttan, 2002; Self and Grabowski, 2007).

The fact that agricultural production is subject to weather and climate conditions constrains productivity growth and makes it distinctive from other economic activities (Timmer, 1988). Farm price volatility and uncertainty could also discourage agricultural production. Yet, such intrinsic limitations in improving agricultural productivity can be overcome by making modern agricultural inputs available to farm producers and providing institutional/physical infrastructure indispensable in facilitating transactions in input and output markets. Particularly in countries at early stages of economic development, farm producers can improve their productivity simply by using more modern agricultural inputs such as fertilizers or higher-yielding varieties of seeds. In the longer run, investments in R&D for developing productivity-enhancing inputs or adapting inputs/technologies developed elsewhere to local growing conditions would be needed for improving agricultural productivity.

Agricultural growth could be promoted through four stages (Johnston and Mellor, 1961): first, creating the preconditions for agricultural takeoff such as improvements in land property rights, access to markets for agricultural outputs, and an adequate institutional environment for adoption of modern inputs (e.g. seeds, fertilizers, machines); second, encouraging labor-intensive and capital-saving practices in countries at an early stage of economic development; third, providing complementary inputs that encompass agricultural R&D, rural extension-education, agricultural credit, marketing facilities, and rural development agencies; finally, implementing capital-intensive and labor-saving strategies through investments in mechanization, chemical, and biological innovations.

At the global level, agricultural output grew on average by 2.24% annually between 1961 and 2014 (Fuglie, 2018). During the same period, agricultural labor and land growth rates show a lower growth rate, particularly in the period 2001-2014. Agricultural output per worker (labor productivity) grew by 1.31% per year between 1961 and 2014, and, in particular, it accelerated at 2.84% per year during 2001-2014. Growth rate in output per hectare of agricultural land (land productivity) averaged 2.04% per year, and it increased at 2.65% for the period 2001-2014.

Developing countries show a higher upward trend in agricultural output growth (3.34% per year) compared to developed countries that registered a growth rate of only 1.19% per year between 1961 and 2014. Land productivity in developed countries grew by 1.43% per year between 1961 and 2014, but it slowed at 1.24% during 2001-2014 (Fuglie, 2018). In developing countries, land productivity grew by 2.91% per year between 1961 and 2014, and it accelerated at 3.31% per year particularly between 2001 and 2014. Labor productivity in industrialized nations grew by an average of 4.12% per year during 1961-2014, but it decelerated at 4.02% between 2001 and 2014. In developing countries, labor productivity grew 2.16% per year between 1961 and 2014, and it accelerated to 3.55% particularly between 2001 and 2014. The growth rate in world agricultural total factor productivity (TFP) was an average of 0.97% per year during 1961-2014, and it increased to 1.71% per year particularly between 2001 and 2014 (Fuglie, 2018). It was associated with a steady growth of agricultural output and a slowdown in growth rates of agricultural inputs—mainly labor and land. In developed countries, agricultural TFP grew at an average of 1.61% per year between 1961 and 2014, and it accelerated at 2.01% per year during 2001-2014. In developing countries, agricultural TFP grew 1.36% per year over 1961-2014, and it increased to 1.93% per year particularly over 2001-2014. The main source associated with the increase of agricultural TFP in developing countries was higher investments in agricultural R&D.

At the regional level in Latin America, the average agricultural output growth was 2.51% annually between 1960 and 2000 (Bravo-Ortega and Lederman, 2004). Agricultural growth in Colombia was 2.58% per year, slightly higher compared to the average of the Latin American and Caribbean (LAC) countries, although it was lower than Bolivia, Paraguay, Brazil, and Guatemala that grew over 3.36% per year (Bravo-Ortega and Lederman, 2004). The U.S. Department of Agriculture (USDA) (2018) also reported a similar growth rate in agricultural output for Colombia at 2.5% per year between 1961 and 2015. Despite the seemingly good performance of the agricultural sector, studies suggest that partial factor productivity (PFP) and TFP growth performance in Colombia was not as good as in other LAC countries (Coelli and Rao, 2005; OECD 2015; Ludena 2010; Jiménez, Abbott, and Foster 2018). Although the growth rate in agricultural productivity has been increasing in the last decades, it is low compared to other countries in the region, including Brazil, Chile, Ecuador, and Peru (OECD, 2015; Pardey et al., 2010; Coelli and Rao, 2005; Ludena, 2010; Pfeiffer, 2003; Nin Pratt et al., 2015; Bravo-Ortega and Lederman, 2004; Jiménez et al., 2018). Agricultural TFP, labor, and land productivity in Colombia grew about 2%, 1.9%, and 2% per year, respectively. (Table 1 summarizes studies analyzing productivity growth in Colombia).

Lozano-Espitia and Restrepo-Salazar (2016) show that lack of infrastructure (irrigation and drainage systems, roads, storage and marketing facilities, electricity, and telecommunications) in Colombia hindered the operation of markets, investment in agricultural projects, and agricultural productivity growth. They report that the national coverage of irrigation districts in Colombia is low (5.6%) compared to regional countries such as Mexico (66.1%), Chile (44.3%), Peru (40%), Brazil (18.4%), or Argentina (14.7%). The quality and quantity of roads are not in good conditions causing a low land use rate for crop production; only 12.7% of national roads are paved in Colombia, lower than Mexico (36%), Chile (23%), and Argentina (23%). Likewise, the limited access to marketplace centers from rural areas results from the deficient road infrastructure, which,

in the long run, means higher transaction costs and higher travel time for farmers.

The majority of biological, mechanical, chemical, and information improvements in agricultural production have been possible through public and private expenditures in agricultural R&D (Alston et al., 2010; Piesse and Thirtle, 2010). These agricultural innovations have not only led to overcoming technical inefficiency, but also to achieving technological improvement; therefore, agricultural R&D expenditure has been associated with productivity growth in the short- and long-terms (Alston et al., 2010; Färe et al., 2008; Khan et al., 2017; Makki et al., 1999; Piesse and Thirtle, 2010).

Table 2. Definitions of Variables and Summary Statistics.

Variable Name	Variable Definition	Units	Mean and SD	Source
<i>Output</i>	Gross agricultural output	Thousands of dollars (constant 2004-2006 international prices)	\$11,282,559 ± \$2,531,713	USDA (2018)
<i>R&D</i>	Public R&D spending	Millions of dollars (constant 2011 international prices)	\$220.58 ± \$40.84	ASTI (2019)
<i>Labor-p</i>	Output value per worker	Thousands of dollars (constant 2004-2006 international prices)	\$3,191.53 ± \$577.74	Calculated based on USDA (2019)
<i>Land-p</i>	Output value per hectare	Thousands of dollars (constant 2004-2006 international prices)	\$2,795.97 ± \$1,051.13	Calculated based on USDA (2018)
<i>Cropland</i>	Arable land plus land in permanent crops	Thousands of hectares	4295.99 ± 730.76	USDA (2018)
<i>Labor</i> ¹	Number of economically active adults in agriculture	Thousands of people: + 15 years, female + male	3509.88 ± 212.32	USDA (2018)
<i>Fertilizer</i>	Consumption of N, P2O5, K2O	Metric tons	609,963.89 ± 179,724.10	USDA (2018)
<i>Machinery</i>	Total stock of farm machinery in 40-CV tractor equivalents	CV=metric horsepower	26,609.01 ± 5,141.57	USDA (2018)
<i>Irrigation</i>	Area equipped for irrigation	Thousands of hectares	821.14 ± 227.08	USDA (2018)

¹ Labor refers to the number of people economically active in agriculture and who are over 15 years old.

There have been changes in the sources of investment in global R&D expenditures. For example, in recent decades, middle-income countries as a whole have been investing more than high-income countries (Pardey et al., 2016). The share of developed countries in global agricultural R&D expenditures dropped from 69% in 1980 to 55% in 2011, while the share of middle-income countries increased from 29% to 43%. Nevertheless, the agricultural R&D expenditure on a per capita basis is much lower in low-income countries than developed countries. For instance, high-income countries invested \$17.73 per person, while least developed countries invested only \$1.51 per capita in 2011. On the other side, there are differences in terms of the sources of investment between middle- and high-income countries. In developed countries, research in biological, chemical, and other technical innovations has been mainly led by private organizations, while in middle-income countries, the public sector is still the main contributor to agricultural R&D (Pardey et al., 2016).

In Latin America, agricultural R&D activity and spending mainly come from national agricultural research institutes (Echeverría, 1998). The large- and medium-sized countries in Latin America tend to have higher R&D expenditures and human capital (Stads and Beintema, 2009). The investment in agricultural R&D in the region increased from \$2.3 billion in 1981 (in 2005 purchasing power parity or PPP dollars) to \$3.0 billion in 2006. In 2006, Brazil, Argentina, and

Mexico accounted for roughly 75% of the region's total spending in agricultural R&D and the same countries hold 70% of agricultural scientists (Stads and Beintema, 2009).

Data

To fulfill the objective of this study measuring the impact of R&D spending on agricultural output and productivity growth in Colombia, we collected data from two primary sources: the USDA and the Agricultural Science and Technology Indicators (ASTI). Definitions of the variables used in this paper and summary statistics are presented in Table 2. Gross agricultural output (*Output*) is the sum of the value of production of 189 crop and livestock commodities. Public R&D spending (*R&D*) is government expenditure in R&D activities within the agriculture sector. Labor productivity (*Labor-p*) is calculated by dividing agricultural output by agricultural labor, and land productivity (*Land-p*) is agricultural output divided by total cropland. Cropland (*Cropland*) refers to arable land plus land in permanent crops. Agricultural labor (*Labor*) corresponds to adults economically active in agriculture. *Fertilizer*¹ refers to the quantity of yearly fertilizer consumption. Farm machinery (*Machinery*) refers to the total stock of machinery in 40-CV tractor equivalents. Area equipped for irrigation (*Irrigation*) refers to agricultural areas purposely provided with water, including land irrigated by controlled flooding.

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As shown in Figure 2, agricultural output in Colombia shows an ascending trend in recent decades except for 2009 and 2010. On average, Colombian agricultural production grew 2% annually for the period between 1981 and 2016 (USDA, 2018). Agricultural labor and land productivity in Colombia also show an upward trend; the output value per worker in Colombia increased from \$2,396 in 1981 to \$3,965 in 2016 while the output value per cropland hectare increased from \$1,498 to \$4,204 for the same period (Figure 3). The annual growth rate of agricultural labor and land productivity averaged 1.6%, and 3.1 %, respectively, over the same period.

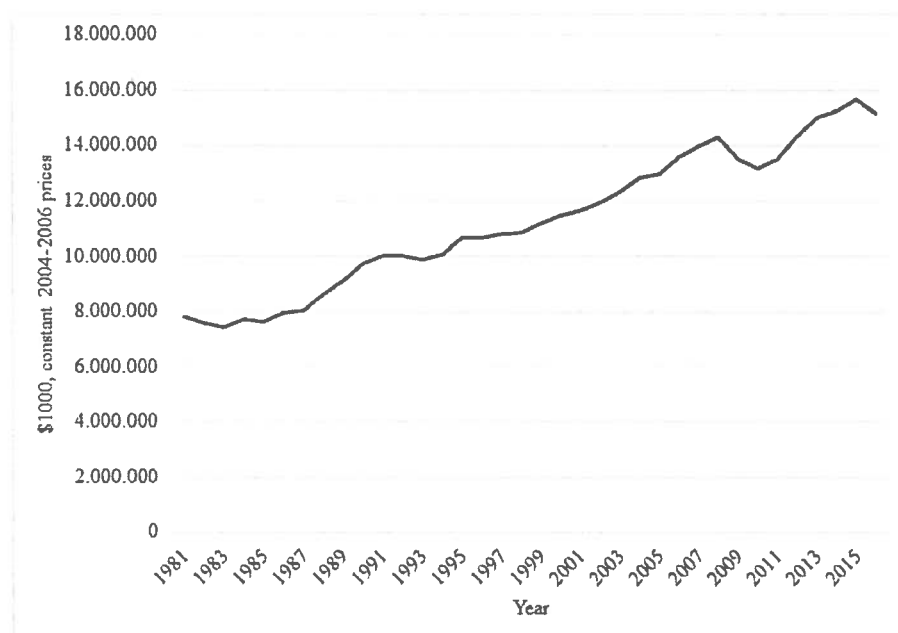


Figure 2. Gross agricultural output of Colombia, 1981-2016.

Source: USDA (2018).

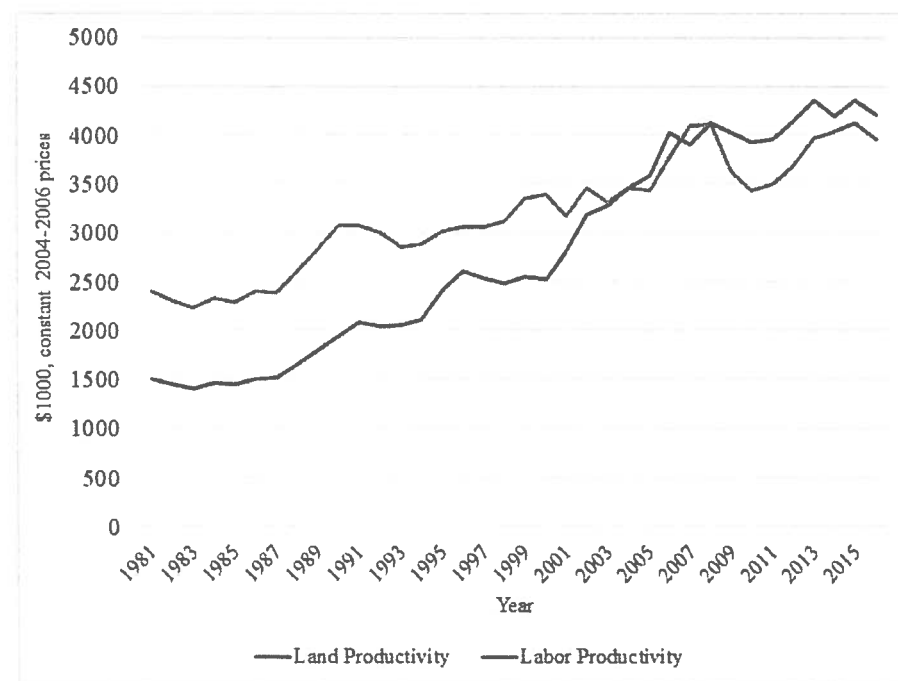


Figure 3. Agricultural labor and land productivity in Colombia, 1981-2016.

Source: Authors' calculations based on USDA (2018).

At first glance, the budget for the major institutions in charge of research, extension, and education for crop and livestock industries in Colombia has increased in the last decades. The combined budget of the Institute of Colombian Agriculture (ICA) and the Colombian Corporation for Agricultural Research (CORPOICA) has increased from \$9 million (in 1993 PPP dollars) at the beginning of the 1960s to \$68 million in 1998. The average annual growth of public expenditures in agricultural research and development was 2.3% per year between 1981 and 2013 (ASTI, 2019). However, the absolute value of agricultural R&D investments has declined. The decline has likely been harmful to the growth potential of Colombian agriculture (Echeverría, 1998; Junguito et al., 2014; Stads and Beintema, 2009). Figure 4 shows annual public spending in Colombia's agricultural R&D 1981-2013. It had a peak investment in 1985 of \$352.44 million and it dropped to \$253.71 million in 2013 (ASTI, 2019). Agricultural labor in Colombia shows a slight increase from 3.2 million people in 1981 to 3.9 million people in 2016. Fertilizer consumption in Colombia has been growing at 4% per year between 1981 and 2016 (Figure 5). It increased from 292,000 metric tons in 1981 to 985,000 metric tons in 2016. The area equipped for irrigation in Colombia increased from 420,000 hectares in 1981 to 1 million hectares in 2016 (Figure 6). The average annual area equipped for irrigation grew at 3% per year 1981-2016.



Figure 4. National spending in agricultural R&D in Colombia, 1981-2013.

Source: ASTI, 2019.

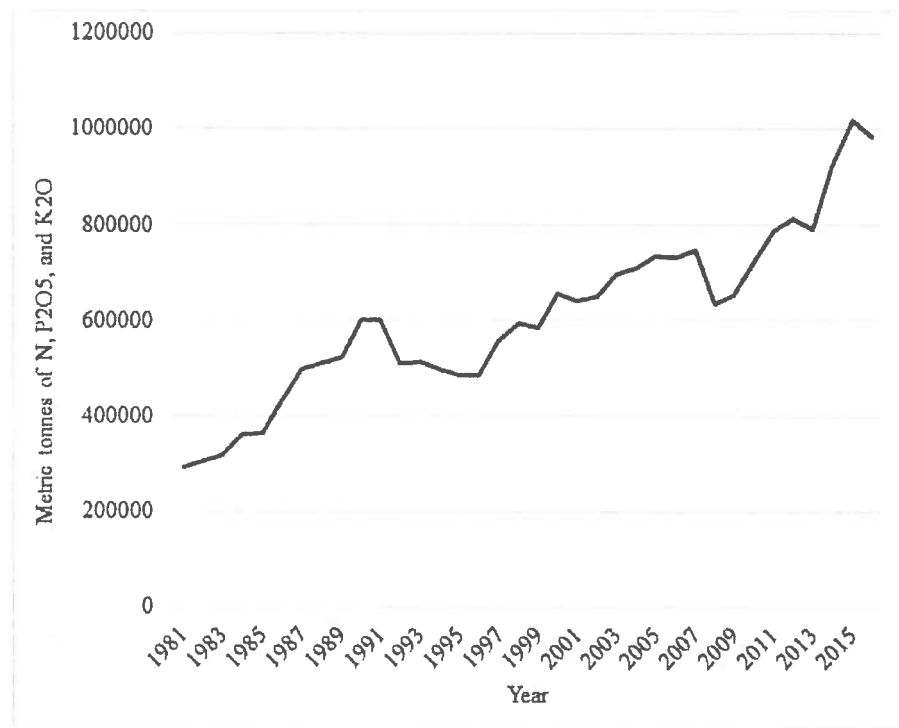


Figure 5. Fertilizer consumption in Colombia, 1981-2016.

Source: USDA (2018).

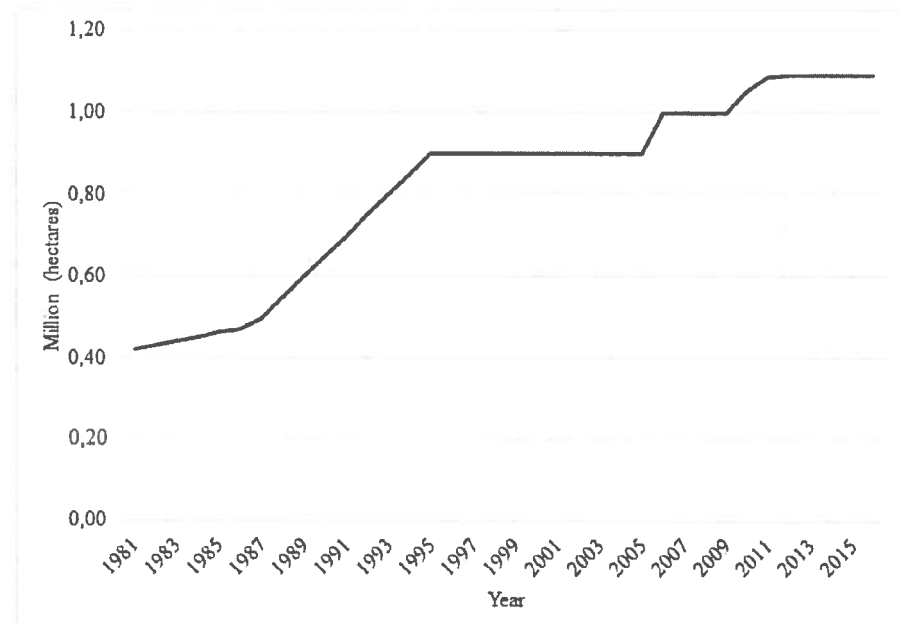


Figure 6. Area equipped for irrigation in Colombia, 1981-2016.

Source: USDA (2018).

A particular aspect in the agricultural transformation in Colombia is the fact that its area of cropland shows a gradual decrease from 5.2 million hectares in 1981 to 3.5 million hectares in 2016 (Figure 7). This fact might be attributed to two factors. First, despite the fact that new agricultural land has been created due to high rates of deforestation, the cleared land has been devoted mainly to the extensive grazing of beef cattle (Graesser et al., 2015; Krause, 2020). Second, historically, Colombia has land use conflicts; specifically, there is an excessive use of land for grazing and an insufficient use of cropland. For example, while 13% of agricultural land should be suitable for pasture, the use in 2012 was about 31% of agriculture land. On the other side, cropland should account for 19% of agricultural land, but the use in 2012 was about 5% of agriculture area (OECD, 2015).

The decline in cropland might be related to the situation of agricultural machinery in Colombia. The total stock of farm machinery reached about 35,000 units (40-CV tractor equivalents) by 1987-1988 but has since decreased. The total stock of farm machinery has leveled off to about 23,000 units between 1995 and 2016 (USDA, 2018) (Figure 8). Historically, crop production in Colombia has been characterized by small-scale farming with low level of adoption of technologies and equipment, with the exception of some crops such as sugar cane and rice (Jiménez et al., 2018). Marín-Usuga, Causa, and Loaiza-Usuga (2016) argue that some agricultural policies have not encouraged agricultural modernization; however, recent policies might help to counter historically low investment in farm machinery and equipment through agricultural credit.

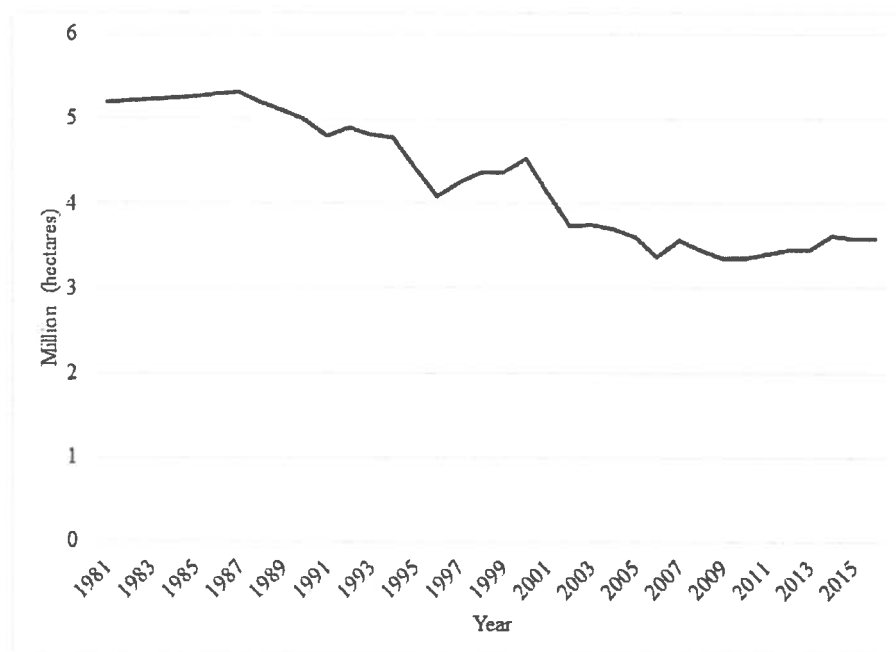


Figure 7. Arable land plus land in permanent crops in Colombia, 1981-2016.

Source: USDA (2018).

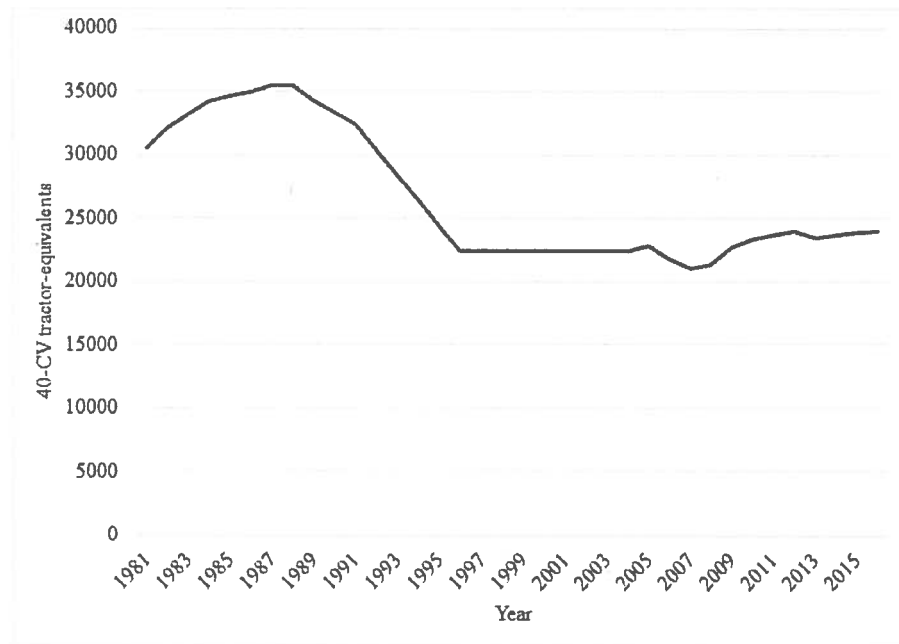


Figure 8. Agricultural machinery in Colombia, 1981-2016.

Source: USDA (2018).

Model Specifications and Estimated Results

Significant and positive effects of R&D on agricultural production have been reported in countries with different stages of development and using distinct ways to measure productivity and to quantify the impact of R&D on agricultural productivity. In the United States, Makki et al. (1999) estimated that a 1% increase in public spending in R&D could increase agricultural productivity by 0.38% using an error correction model (ECM). In the same country, a cointegrating relationship was established between U.S. agriculture growth and R&D expenditure, and an unidirectional causality from agricultural R&D to productivity growth also was found (Färe et al., 2008). Similar results were found in Australia by using ECM (Khan et al., 2017). Additionally, they found long-term impact of public R&D investment and a potential spillover effect of international research expenditures on domestic TFP growth. Suphannachart and Warr (2011) show that the social rate of return in crop R&D is 29.5% in Thailand. Additionally, Nadeem and Mushtaq (2012) estimated that marginal return rate to research in Punjab, Pakistan, is 73%, and a 1% increase in research spending could result in 0.57% increase in agricultural TFP. Highlighting the high explanatory power of public R&D investment in the UK agricultural TFP growth in the last decades, Thirtle et al. (2008) argued that the rate of return (ROR) to R&D can vary depending on R&D lag structure; that is, the ROR may range from 15% to as much as 71%. In short, these studies demonstrate the significant role of R&D spending on agricultural productivity growth in various countries.

Building on the literature, we use the data described in the previous section to estimate the following relationships linking agricultural output, labor, and land productivity to various

explanatory variables in Colombia:

$$(1) \quad Output = f(R\&D, Irrigation, Cropland, Labor, Machinery)$$

$$(2) \quad Labor-p = f(R\&D, Machinery)$$

$$(3) \quad Land-p = f(R\&D, Fertilizer, Irrigation, Machinery)$$

We expect a long-run positive effect of agricultural R&D spending (*R&D*) on the three dependent variables: gross agricultural output, agricultural labor, and land productivity (Khan et al., 2017; Piesse and Thirtle, 2010). In the first specification, agricultural output (*Output*) in Colombia is explained mainly by factors of production including *Labor* and *Cropland*, as well as the area equipped for irrigation (*Irrigation*) and the total stock of farm equipment (*Machinery*). Historically, growth in agricultural production mainly came from expansion in the cultivated area as well as more agricultural workers. In the last decades, however, agricultural productivity has been related to expansion in area irrigated, intensive use of technical inputs (fertilizer and crop chemicals) and improved crop varieties (Ruttan, 2002; Timmer, 1988). The second and third equations deal with agricultural labor and land productivity in Colombia, *Labor-p* and *Land-p*, respectively. We hypothesize that *Machinery*, *Fertilizer*, *Irrigation*, and *R&D* play an important role determining land productivity in Colombia.

We estimate the three equations using the double-log model specification, thus the estimated coefficients representing explanatory variables' relative impacts. Given the time-series nature of our data, we use time-series econometric methodology that involves: (i) checking for stationary properties of the variables; (ii) evaluating whether cointegration exists in the three specifications; and (iii) estimating a vector error correction model. First, we evaluated the stationary and the order of integration of the time series by using the Augmented Dickey-Fuller (ADF) test. Application of regression analysis to nonstationary time series data would result in spurious relationships. We found that the series are non-stationary in their levels, but they become stationary in first order (Table 3). Second, given that empirical literature suggests that there is a long-term relationship between R&D and agricultural productivity, we employ the Johansen cointegration test to evaluate the presence of cointegration. Cointegration suggests a long-term relationship, implying that time-series variables move in tandem (Makki et al., 1999; Suphannachart and Warr, 2011). In equation (1), both the trace test and the max-eigenvalue test show two cointegrating equations at the 5 % significance level (Table 4). In other words, the null hypothesis of no cointegration can be rejected at 5% of significance. In equation (2), we did not find any cointegrating equation (Table 5). In equation (3), the trace test indicates one cointegrating equation at the 5 % significance level (Table 6). The cointegration test results support the solid empirical and theoretical evidence linking R&D spending and gains in productivity across various regions of the world (Färe et al., 2008; Khan et al., 2017; Makki et al., 1999; Nadeem and Mushtaq, 2012; Suphannachart and Warr, 2011; Thirtle, Piesse, and Schimmelpfennig, 2008). They also confirm the significant role of R&D spending in determining agricultural productivity specifically in Colombia, a middle-income country in need of

growing its agricultural sector to promote rural development as well as pave the way for upgrading its economy to a higher level.

Table 3. Testing for Non-stationarity.

Variable	Level [<i>t</i> -statistics]	First Difference [<i>t</i> -statistics]
ln Output	-0.59	-4.41**
ln Labor	-1.56	-6.50**
ln Cropland	-0.86	-5.29**
ln Machinery	-1.91	-2.60*
ln Fertilizer	-1.52	-5.17**
ln Irrigation	-2.22	-2.88**
ln R&D	-2.97*	-6.93**
ln Labor- <i>p</i>	-0.98	-4.94**
ln Land- <i>p</i>	-0.67	-4.90**

All variables are in natural logarithms. * and ** denote the rejection of the null hypothesis at the 10%, and 5% level, respectively.

Table 4. Cointegration Test (Equation 1).

Series Tested: *Lnoutput Lnresearch Lnirrigation Lncropland Lnlabor Lnmachinery*

Hypothesized				5%
No. of CE(s)	Eigenvalue	Statistic	Critical Value	Prob.**
Trace test				
None *	0.745	126.24	95.75	0.01
At most 1 *	0.633	79.66	69.82	0.01
At most 2	0.552	45.58	47.86	0.08
At most 3	0.243	18.21	29.8	0.55
At most 4	0.177	8.71	15.49	0.39
At most 5	0.059	2.08	3.84	0.14
Max-eigenvalue test				
None *	0.745	46.58	40.08	0.01
At most 1 *	0.633	34.09	33.88	0.04
At most 2	0.552	27.37	27.58	0.05
At most 3	0.243	9.5	21.13	0.79
At most 4	0.177	6.63	14.26	0.53
At most 5	0.059	2.08	3.84	0.14

All variables are in natural logarithms. **MacKinnon-Haug-Michelis *p*-values. * Rejection of the hypothesis at the 0.05 level.

Finally, we employ a vector error correction (VEC) model because it works based on the presence of cointegration and stationarity of the variables under consideration. The VEC model has been a useful econometric technique in studying the role of R&D on agricultural productivity growth (Färe et al., 2008; Khan et al., 2017; Lee et al., 2017; Makki et al., 1999; Nadeem and Mushtaq, 2012; Suphannachart and Warr, 2011). In using the VEC model, we incorporated lagged

values of the variables. The lag length was based on Akaike and Schwartz Criterion and these two statistics show that the optimum lag length is two for the three specifications. One component in the VEC model is the error correction term, which refers to the one-period lagged value of the error term from the cointegrating equation (Khan et al., 2017). Basically, it shows the validity of a long-run equilibrium relationship among the analyzed variables in the cointegration analysis. Table 7 shows the test results for the VEC model of the three specifications.

Table 5. Cointegration Test (Equation 2).

Series Tested: Ln_{labor}-p Ln_{research} Ln_{machinery}				
Hypothesized	5%			
No. of CE(s)	Eigenvalue	Statistic	Critical Value	Prob.**
Trace test				
None	0.388	28.03	29.8	0.07
At most 1	0.191	11.32	15.49	0.19
At most 2 *	0.112	4.08	3.84	0.04
Max-eigenvalue test				
None	0.388	16.71	21.13	0.18
At most 1	0.191	7.25	14.26	0.46
At most 2 *	0.112	4.08	3.84	0.04

All variables are in natural logarithms. **MacKinnon-Haug-Michelis p-values. * Denotes rejection of the hypothesis at the 0.05 level.

Table 6. Cointegration Test (Equation 3).

Series tested: Ln_{land}-p Ln_{research} Ln_{irrigation} Ln_{fertilizer} Ln_{machinery}				
Hypothesized	5%			
No. of CE(s)	Eigenvalue	Statistic	Critical Value	Prob.**
Trace test				
None *	0.575	76.73	69.82	0.01
At most 1	0.518	47.58	47.86	0.05
At most 2	0.277	22.76	29.8	0.25
At most 3	0.227	11.71	15.49	0.17
At most 4	0.082	2.93	3.84	0.08
Max-eigenvalue test				
None	0.575	29.15	33.88	0.16
At most 1	0.518	24.82	27.58	0.1
At most 2	0.277	11.05	21.13	0.64
At most 3	0.227	8.79	14.26	0.3
At most 4	0.082	2.93	3.84	0.08

All variables are in natural logarithms. **MacKinnon-Haug-Michelis p-values. * Rejection of the hypothesis at the 0.05 level.

Although the VEC approach shows a positive effect of R&D spending on agricultural output ($\beta = 0.01$), labor productivity ($\beta = 0.05$), and land productivity ($\beta = 0.05$); these coefficients were not statistically significant. This finding could be explained by the fact that the effects of R&D are

usually evident in the long-term, but in this study too few lagged periods were used due to data constraints. Investment in R&D could take years to impact agricultural performance. Alston et al. (2010) argue that the development of a new variety in crops might take 5 to 10 years and the peak of benefits from an initial R&D investment would be reached in a 15 to 25 year range. Likewise, Piesse et al. (2011) mention that the lag length on public R&D is usually long, taking 27 years as a reference. The error correction term, in the VEC model, in the first and second specification was statistically significant and negative (-0.60 and -1.24, respectively), suggesting that the equations move towards a long-run equilibrium (Khan et al., 2017). The fact the error correction model is statistically significant implies that R&D has some statistically significant role via its presence in the VEC model. In contrast, it was not significant in the third equation (-0.08).

Table 7. VEC Results.

Variable	D(Output (-2))	D(Labor-p (-2))	D(Land-p (-2))
	Parameter [<i>t</i> -statistics]	Parameter [<i>t</i> -statistics]	Parameter [<i>t</i> -statistics]
ECM	-0.6 [-3.96]***	-1.24 [-3.56]**	-0.08 [-0.76]
D(Output (-2))	0.44 [2.07]**	-	-
D(Labor-p (-2))	-	0.64 [2.68]**	-
D(Land-p (-2))	-	-	-0.09 [-0.37]
D(R&D (-2))	0.01 [0.36]	0.05 [0.94]	0.05 [0.07]
D(Irrigation (-2))	0.07 [0.33]	-	0.87 [1.79]
D(Cropland (-2))	-0.1 [-0.93]	-	-
D(Labor (-2))	-0.49 [-2.84]**	-	-
D(Machinery (-2))	0.07 [0.31]	0.51 [1.18]	-0.33 [-0.61]
D(Fertilizer (-2))	-	-	0.22 [1.29]
Constant	-0.01 [-0.45]	-0.01 [-0.28]	-0.1 [-0.14]
R-squared	0.96	0.51	0.38
S.E. of regression	0.69	0.05	0.06
F-statistic	3.11**	3.59***	1.13

All variables are in natural logarithms. ***, **, and * imply significance at 1%, 5%, and 10%, respectively. D stands for first difference.

Discussion and Conclusions

Theoretical and empirical literature suggests that investments in R&D brought about biological, mechanical, and technical innovations in agricultural production. Labor productivity growth mainly depends on mechanical technology while land productivity growth depends on biological and chemical innovations. Such technological changes prove to be the keys for agricultural transformation, poverty reduction, and other economic improvements.

In Colombia, the agricultural R&D spending growth rate has been reduced and even turned negative in recent years. Given that there is not much information about the role of agricultural R&D in Colombian agriculture (Beintema et al., 2000; Junguito et al., 2014), this study aimed at evaluating the role of R&D expenditures in determining agricultural output and productivity. Specifically, this study used time-series models to estimate the effect of R&D expenditure and other factors (land, labor, fertilizer, machinery, and irrigation) on agricultural output, labor, and land productivity in Colombia for the period of 1981–2016. The Johansen cointegration test suggests that there is a long-run relationship between R&D spending with agricultural output and land productivity in Colombia. This result is in spite of the decreases in R&D spending during some points in the study period of 1981–2016. However, the VEC approach did not confirm that finding. The mixed results about the effects of R&D spending in the Colombian case may be related to the particular way agricultural labor and land productivity were measured in our study. Further research is needed using different sets of data and estimation techniques, and researchers may quantify the impact of R&D on agricultural productivity in Colombia using more accurate measurements of productivity such as total factor productivity (TFP), which is a more comprehensive measure than the partial factor productivity measures (Rada, Helfand, and Magalhães, 2019). Moreover, in order to properly capture the long-run effects of R&D, it would be desirable to use a longer time period. Additional control variables could be included such as weather, and institutional- and infrastructure-related variables. Similarly, it should be useful to analyze the influence of R&D on production efficiency at the disaggregate farm level. It is expected that positive effects of public research spending at the farm level could justify greater agricultural R&D budget allocation from the Colombian state.

Although this paper focused on examining the role of agricultural R&D, there are other factors needed in order to fully realize the positive role of R&D spending in improving agricultural productivity in Colombia. In particular, even though land reform efforts in the last decades have increased rural plot size, decreased land inequality, narrowed landholding dispersion, and improved human development, and political and institutional reforms are still needed, particularly in the distribution of political power necessary to achieve a more equal income distribution and economic growth (Faguet et al., 2016). Colombia is one of the regional countries with the highest amount of land concentration (Guereña, 2017). The unequal distribution of land is translated into social inequality; that is, high land concentration is associated with hindrance in democratization, investments in human development, and economic growth (Faguet et al., 2016). Therefore, political and institutional improvements may be necessary to accelerate agricultural development in Colombia. In addition, the improvement in physical infrastructure including roads, irrigation and drainage systems, storage and marketing facilities, electricity, and telecommunications could be

equally important. Evidence suggests that it would boost agricultural productivity, improve operation of markets, and encourage investment in agricultural projects (Lozano-Espitia and Restrepo-Salazar, 2016). For instance, changes in tertiary road design and maintenance could bring new economic and social opportunities in rural areas in Colombia (Correa, 2017). The availability of agricultural inputs such as machinery is also important. However, agricultural machinery in Colombia increased until 1988 and then it suffered an abrupt fall (USDA, 2018). This situation could have been a constraint in the transformation of Colombia's agriculture. Therefore, the government should facilitate the access to agricultural inputs including machinery, fertilizer, improved seeds, and other agricultural technologies.

Since the above-mentioned factors are largely of institutional and public natures, the state is the primary entity responsible for providing them. Agricultural R&D investment should be the undertaking of the state, too. Colombia, as a middle-income country, is in need of sustained economic growth through technological innovations so as to overcome the challenges in joining the group of high-income countries. Agricultural growth through technological improvements should be the precondition of such economic growth and the state has a pivotal role to play in the process.

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