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The benefits from public agricultural research in Uruguay

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We use newly constructed data to model and measure agricultural productivity growth and the returns to public agricultural research conducted in Uruguay over the period 1961–2010. We pay attention specifically to the role of levy-based funding under INIA, which was established in 1990. Our results indicate that the creation of INIA was associated with a revitalization of funding for agricultural R&D in Uruguay, which spurred sustained growth in agricultural productivity during the past two decades when productivity growth was stagnating in many other countries. The econometric results were somewhat sensitive to specification choices. The preferred model includes two other variables with common trends, a time-trend variable and a proxy for private research impacts, as well as a variable representing the stock of public agricultural knowledge that entailed a lag distribution with a peak impact at year 24 of the 25-year lag. It implies a marginal benefit-cost ratio of 48.2, using a real discount rate of 5 per cent per annum and a modified internal rate of return of 24 per cent per annum. The benefit-cost ratio varied significantly across models with different lag structures or that omitted the trend or the private research variable, but across the same models, the modified internal rate of return was very stable, ranging from 23 per cent per annum to 27 per cent per annum. These results suggest that the revitalized investment in research spending under INIA has been very profitable for Uruguay and that a greater rate of investment would have been justified.

Key words: agricultural productivity, levy-based funding, public agricultural R&D, rates of return, Uruguay.

1. Introduction

Around the world, public support for investments in agricultural R&D continues to wane in spite of both consistently high reported rates of return to agricultural R&D and emerging evidence of slowing rates of agricultural productivity growth (Pardey and Alston 2010). One approach for economists, to address this persistent paradox, is to provide more complete and

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more compelling evidence about the economic implications of alternative agricultural science policies. Formal studies of national agricultural research systems (NARSs), agricultural productivity patterns and the returns to agricultural R&D investments have mostly been undertaken for high-income countries for which relatively good data sources and other resources are available, or for the large middle-income countries, such as China and Brazil (Alston *et al.* 2000). Little is known about the performance of the NARSs in the vast number of countries that do not belong in either of these categories.

Uruguay is an example: as well as being of interest in its own right, and as an example of a small middle-income country, the NARS of Uruguay has some interesting characteristics that make it worthy of study as a potential source of more general lessons. In Uruguay, public agricultural research was transformed in 1990, with the introduction of a new institution, the National Institute for Agricultural Research (INIA), to be supported substantially using funds generated from a farm sales tax of 0.4 per cent, applicable on the sales of cattle, sheep, wool, unprocessed hides, pigs, grains, milk, poultry, honey, timber and exports of fresh fruits and vegetables, flowers and seeds. In 2010, a review of INIA was undertaken, to evaluate its accomplishments in its first 20 years (Pareja *et al.* 2011). Information gathered in that review provides the foundation for the work in this article and the longer Working Paper by Bervejillo, Alston and Tumber (BAT 2011), which provides more detail on the history and structure of Uruguay's agriculture, as well as its research institutions and investments, productivity patterns and data used in the analysis.

We begin by describing the main changes in Uruguayan agriculture during the past 30–40 years, including the economic history of agricultural research institutions and investments in Uruguay. This provides some context for a formal analysis of growth in agricultural inputs, outputs and productivity, which is presented next. The indexes of multifactor productivity (MFP) are Fisher Ideal discrete approximations to Divisia indexes that reflect a careful effort to account for variation over time in the composition of the aggregates of inputs and outputs, and thereby minimize the role of index number problems. These elements are combined in an econometric model of MFP in Uruguayan agriculture over the period 1980–2010, as a function of public investments in agricultural R&D over the years 1960–2010, using an approach that parallels closely that of Alston *et al.* (2010). The results are expressed as benefit-cost ratios and *modified* internal rates of return, as suggested by Alston *et al.* (2011).

As argued by Alston and Pardey (2001), accurate attribution is always a challenge in this kind of work, whether we are attempting to attribute benefits to Uruguayan public agricultural research investments, versus other sources, or to identify impacts from the creation of INIA. The general attribution problem may be more pronounced for a small country, such as Uruguay, which is likely to benefit substantially from international agricultural research and technology spillovers from its large near neighbours, Brazil and

Argentina, as well as other general sources of agricultural technology such as the United States and the international agricultural research system (including the CGIAR centres). In the penultimate section of the paper, we discuss the interpretation of our results. To illustrate the role of fundamental factors, we compare the resulting estimates with simple approximations that abstract from the detail of the temporal aspects, and apply alternative attribution rules. We also look informally for evidence of an acceleration or slowdown of productivity growth that might be attributable to the creation of INIA. The paper ends with a brief conclusion, which summarizes our main findings and their implications.

2. Agriculture in Uruguay

Uruguay is one of the most economically developed countries in South America, with a Gross Domestic Product (GDP) per capita of $12,000 in 2010, with GDP defined as the value of final goods and services produced within a country. It is a relatively urbanized nation in which 92 per cent of its 3.5 million inhabitants live in urban areas; more than half live in the capital, Montevideo and its metropolitan area. Uruguay has about 15 million hectares of agricultural land, of which, at present, 1.8 million hectares are cropland, 1 million hectares are forest land, 1 million hectares are cultivated pastures, and the rest, 11.2 million hectares are natural grasslands, improved pastures and natural forests. Bordered by Brazil to the north, Argentina to the south and west and the Atlantic Ocean to the east, Uruguay is spread across a latitude of 30–35 degrees south (a range comparable to that of New South Wales), and its agriculture is based primarily on a mixture of dry-land cropping and grazing that is similar in many ways to that of southern Australia.

Developments in Uruguay's agriculture during the past 40–50 years have reflected changes in national policies and political regimes, along with broader developments in the global economy and the markets for agricultural products. Many of these changes will have contributed substantially to changes in agricultural production and productivity, with impacts that are difficult to identify and separate from those attributable to technological innovation derived from investments in research and extension, especially in view of the fact that the roles of innovation and other factors are synergistic.

The changes were multifaceted. During the 1970s, and especially after 1978, a process of deregulation of markets and exports took place. A state-owned slaughterhouse was closed and the state monopoly on the Montevideo beef market was ended. Domestic prices of beef and hides were liberalized, and an import tariff of 30 per cent was set for agricultural products. Import tariffs on capital goods and intermediate inputs were eliminated. Export taxes were reduced or eliminated. Subsidies on fertilizers were eliminated. The government facilitated industry-funded export promotion by providing institutional support and tax incentives, especially for barley, citrus, rice and dairy. In 1987, the Forestry Law was passed, which entailed large subsidies and tax exemptions for forestry plantations. The industry developed quickly, with large foreign investments, first in plantations and second in pulp-processing mills. The diversion of land to forestry production has come mainly at the expense of the grazing industry. In 1991, the Treaty of Asunción launched the MERCOSUR customs union, which established a plan to remove tariff barriers among Argentina, Brazil, Paraguay and Uruguay, and established a common external tariff. New agricultural policies were set in place: live cattle exports were allowed; government-owned stocks of frozen beef (used for price regulation) were eliminated; the processing industry was deregulated even more, which resulted in increased competition within the industry and a process of modernization of slaughter plants.

3. Agricultural research institutions and investments

Uruguay's public agricultural research institutions and their investment patterns have undergone significant changes during the past half-century, in parallel with changes in agriculture and the broader economy, as discussed in detail by INIA (2009), Beintema *et al.* (2000), and Stads *et al.* (2008) and summarized by BAT (2011). The first agricultural research centre in Uruguay ('La Estanzuela', in the department of Colonia) was founded in 1919, and for the next forty years, this Experiment Station was the predominant form of public agricultural research activity; it emphasized plant breeding. Agricultural research and technology transfer were transformed significantly during the 1960s, through four institutions: the Center for Agricultural Research (CIAAB), the College of Agriculture of the University of the Republic, the 'Plan Agropecuario' and the Uruguayan Wool Secretariat. However, from 1973 until 1985, under the military dictatorship, public agricultural research was neglected, and many researchers abandoned their careers. Public investments in agricultural research diminished.

3.1. Institutional reforms

In 1986, the new administration changed the organizational structure of the MGAP and created the Directorate of Technology Generation and Transfer (DGTT).[1] In 1989, the Parliament approved the creation of the National Institute of Agricultural Research (INIA), which began operations in 1990 based on the existing infrastructure of the CIAAB and with a large fraction of its personnel. The legislation established that INIA would be funded by the private sector with a matching amount provided by the government. The industry funds would come from a farm sales tax of 0.4 per cent, applicable on the sales of cattle, wool, unprocessed hides, pigs, grains, milk, poultry,

[1] The Ministry of Livestock and Agriculture (MGA) was renamed the Ministry of Livestock, Agriculture and Fisheries (MGAP) with the addition of what was at that time the National Institute of Fisheries.

honey, timber and exports of fresh fruits and vegetables, flowers and seeds. The private sector would hold two seats on the board of four directors, the other two being appointed by the Ministry of Agriculture, of which one is designated president of the board.[2] It was determined that 10 per cent of the total budget (the collected sales tax plus the government matching funds) had to be allocated to research projects developed by other organizations—the Fund for Agricultural Technology Promotion (FPTA).

In 1988, the government of Uruguay signed a contract with the Inter-American Development Bank (IDB) to execute a project on 'Agricultural Technology Generation and Transfer' that would be funded partly by the IDB ($19.3 million) and partly using public funds ($10.4 million). The project would be administered by the DGTT, and its main goal was to strengthen the system of agricultural technology generation and transfer in order to improve agricultural productivity and increase market competitiveness and revenues. The strategy was to develop technologies suitable for each region of the country, to develop a methodology for rural extension and to establish an effective mechanism of technology diffusion (IDB, 1987). Owing to some initial delays and the fact that the new institution (INIA) was just starting to operate, the IDB project did not start until late in 1989, and the transfer of its rights and liabilities to the newly created INIA occurred in April 1990. By the end of the project, in 1996, more than $20 million had been spent on fixed capital investments (new facilities, new laboratories); $2.2 million was applied to capacity building, increasing the number of researchers with post-graduate degrees; and $4.3 million was used for other items. A new IDB project was signed in 1998, with the goal of developing new research programs and to acquire new equipment. This time the IDB contributed $6.3 million and Uruguay's government, $3.3 million. Small amounts were allocated to competitive grants open to non-INIA research organizations.

The Uruguayan Wool Secretariat (SUL) was created in 1966 specifically to address sheep production technologies, including breeding, husbandry and flock management. The SUL is funded by a tax on wool exports that was originally set at 0.3 per cent of the free-on-board (FOB) value. This levy was increased to 0.6 per cent in 1969, 1.2 per cent in 1970 and 1.8 per cent in 1971, but has been held at 1.6 per cent since the mid-1970s. SUL also obtains part of its funds from selling services to farmers. The SUL has been negatively affected by the decline of wool exports. The levy applies to rough wool

[2] The four directors are all actually appointed by the Ministry of Agriculture. Two are appointed directly by the minister, or head of the Ministry, one of which acts as president of the board. The other two are nominated or proposed by the private sector, but the Ministry officially designates them. The 'private sector' in this case means five farmers' organizations: the Rural Federation, the Rural Association, the Federation of Ag-Cooperatives, the Federation of Agricultural Experiment Regional Centers, and the National Commission of Rural Promotion. The first two organizations, which traditionally represent cattle farmers, propose one nominee, and the other three organizations, which mostly represent medium or small farmers, propose the other one.

exports. If wool is exported clean or in tops, an adjustment is made to the rate. At present, the effective rate is equivalent to 0.8 per cent of the total export FOB value of wool, regardless of the type. This is equivalent to approximately 70 per cent of the SUL annual budget, which is about $2.5 million. However, a large portion of SUL's funds has been devoted to promoting Uruguayan wool in international markets. At present, SUL maintains a small number of researchers (8) and extension staff (21) with a limited budget for research programs.

The University of the Republic, with its Colleges of Agriculture and Veterinary Medicine, is the second largest agricultural R&D institution of the country. Although its budget is mostly allocated to teaching activities, it has a large number of full-time professionals that devote between 10 and 50 per cent of their time to research activities. Current annual expenditure by the Colleges of Agriculture and Veterinary Medicine, including teaching and research activities, is $30 million. Of the total expenditure by the Colleges, we estimate that, at different times, between 5 and 25 per cent was allocated to agricultural research.

What seems to have been developing during the past 10 years is private research. Data on this segment are not available so it is somewhat difficult to assess the importance of private agricultural research within the general framework. Several multinational corporations such as Monsanto, Pioneer and Syngenta have their own testing fields for new crop varieties. Some new varieties (corn, wheat, soybeans) are released first in Argentina or Brazil and then evaluated in Uruguay. In the past, the main private firm conducting field trials was the brewery FNC ('Fábricas Nacionales de Cerveza'), which played an important role in developing new varieties of barley. Also in the private sector, several organizations have supported research and have done technology transfer.

3.2. Research investments

Details on spending on public agricultural research by the main spending agencies and in total are provided by BAT (2011, Appendix Table B-1). This total includes CIAAB/INIA, the Plan Agropecuario, and an estimated share of the total expenditures by the Colleges of Agriculture and Veterinary Medicine allocated to research. The Wool Secretariat was not included because it was not possible to quantify the amount of funds used annually for research, but the amounts were small. Figure 1 shows the pattern of total (deflated) spending and its distribution among agencies over time. Annual spending on public agricultural research in Uruguay has increased from the equivalent of US$1.1 million in 1961 to $38.5 million in 2010. In domestic currency terms, after adjusting for currency reforms and inflation, the total grew by a factor of four, from 131.5 million pesos in 1961 to 550.3 million pesos in 2010 (constant 2005 values). But the growth was not uniform over time, and the balance among spending agencies varied significantly.

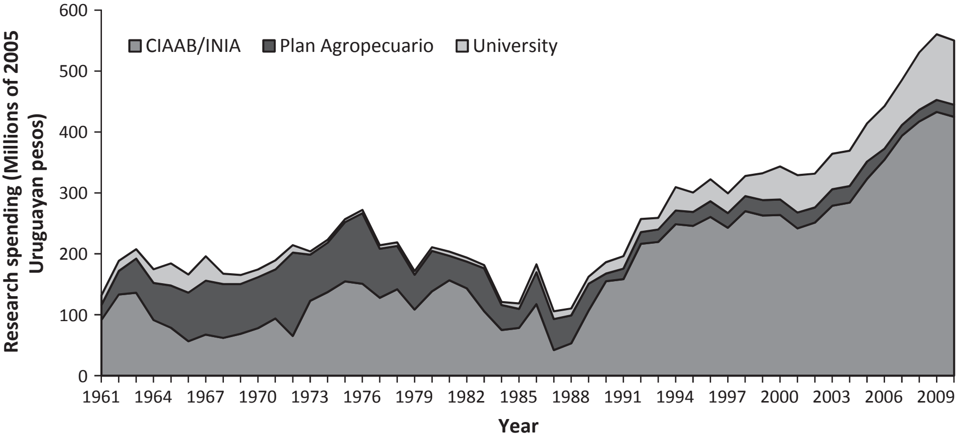

Figure 1 Spending on agricultural research and extension by spending agency, 1961–2010. Source: BAT (2011). Notes: 'University' expenditures are the estimated shares of the College of Agriculture and the College of Veterinary Medicine budget allocated to research activities.

Total spending fluctuated around a rising trend through the 1960s and early 1970s until it dropped precipitously, from 272.2 million pesos in 1976 to 105.8 million pesos in 1987 (constant 2005 values). Beginning in the early 1990s, however, total expenditure was revitalized: it grew in real terms during the 1990s by 6.3 per cent per year and in the 2000s by 4.8 per cent per year. The lion's share of that growth has been in the expenditure by INIA (formerly CIAAB) and the University (Colleges of Agriculture and Veterinary Medicine). From the mid-1960s, the share of the Plan Agropecuario increased significantly, while the University share decreased from 20 per cent to a minimum of 2 per cent in 1974/1975. Conversely, after 1990, the share of the Plan decreased to its current 3.6 per cent, while the University increased to reach almost 20 per cent of the total. Since its foundation, INIA has accounted for between 74 and 82 per cent of the total public expenditures on agricultural R&D.

On balance, the evidence would suggest that the institutional reform in 1990, to create INIA, was effective in revitalizing the total funding available for public agricultural research and extension in Uruguay, enhancing spending both within INIA itself and in the University. The real growth in spending during the recent decade is more particularly remarkable when compared with the generally sluggish public agricultural research spending performance by most countries in recent times (e.g. see Pardey and Alston 2010 and Byerlee 2011). What remains to be seen is whether that investment has yielded a favourable return. We turn to that question next, but with two cautions in mind: first, given long research lags, it may be too early to expect to have seen much impact from investments undertaken since the INIA initiative; second, given the potential roles of spillovers from other countries, it may be difficult to identify contributions by INIA or other public sector entities in Uruguay, let alone separately identify a contribution by INIA.

4. Aggregate inputs, outputs and multifactor productivity

Multifactor productivity in Uruguay's agriculture was estimated using chained Fisher indices of quantities of outputs and inputs used in production. MFP is defined as the ratio of the Fisher index of the aggregate quantity of output to the Fisher index of the aggregate quantity of inputs. This study makes use of relatively detailed data on 39 categories of outputs and 24 categories of inputs over the 30-year period, 1980–2010, which were compiled specifically for this purpose. Few studies of agricultural production and productivity have had access to such detailed data in long time series. The use of detailed, disaggregated data of this nature, combined with the use of a discrete approximation of a Divisia index, can be expected to minimize index number biases. However, as is always true, the data were incomplete or less than ideal in some aspects, and simplifying assumptions must be made to address such deficiencies. In some cases, it was necessary to interpolate between census years to complete series with missing observations. Conventional approaches were used to derive measures of capital and capital service flows and the like. BAT (2011) provide details on these approaches and procedures adopted to deal with missing observations, and complete tables of the measures of prices and quantities of inputs and outputs and productivity. Table 1 summarizes the growth rates of the three series – output, input and MFP – over the three decades, and Figure 2 plots the indexes of quantities of inputs, outputs and productivity.

4.1. Outputs

Over the 30 years from 1980 to 2010, the index of output from Uruguayan agriculture increased from a base of 100 to 243.8, at an annual average rate of 3.0 per cent. The crop sector (including forestry) grew relatively quickly, by 4.7 per cent per year, reflecting in particular the growth in output of soybeans and forestry products, while the livestock sector grew by 1.7 per cent per year. As a result of these trends, crops as a share of the value of production increased from 35.2 per cent in 1980 to 51.3 per cent in 2010. The 30-year annual averages conceal some variation over time in the growth rates. The

Table 1 Indexes of output, input and multifactor productivity, 1980–2010

Year	Output quantity			Input quantity				Multifactor productivity
	Crops	Livestock	Total	Labour	Capital	Other	Total	
Average annual percentage growth rate								
1980–1990	3.3	2.0	2.4	−0.6	−0.4	1.1	−0.1	2.5
1990–2000	2.8	1.7	2.2	−1.0	0.4	2.6	0.5	1.6
2000–2010	8.1	1.3	4.4	3.0	0.7	4.4	2.2	2.2
1980–2010	4.7	1.7	3.0	0.4	0.2	2.7	0.9	2.1

Notes: See notes to Appendix Tables A-1 and A-2 in BAT (2011).

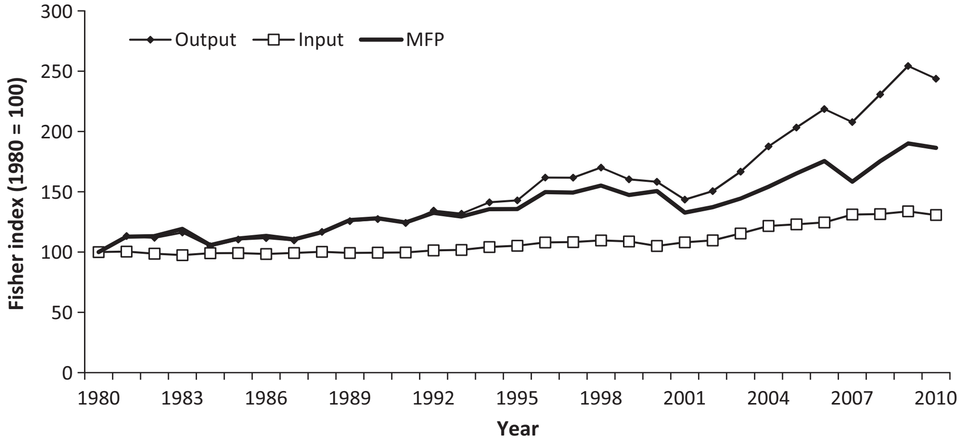

Figure 2 Growth in inputs, outputs and multifactor productivity, 1980–2010.

decades of the 1980s and 1990s showed a relatively flat production trend, with slower growth in output of both crops and livestock during the 1990s than in the 1980s. Growth of livestock production slowed even more, to 1.3 per cent per year, but crop production grew much more quickly, by 8.1 per cent per year in the most recent decade, such that aggregate output grew by 3.0 per cent per year.

4.2. Inputs

The use of inputs also evolved unevenly over time, generally growing less quickly than output, and with some shifts in the balance among input categories. These changes reflect a combination of farmers responding to relative price movements and adopting innovations, particularly technologies that substitute chemicals and machinery for land and labour. Total input use was essentially flat during the 1980s, but began to trend up in the early 1990s, and the rate of growth accelerated during the 2000s. The three categories showed similar patterns of growth rates increasing from decade to decade, but with differences among them reflecting a general substitution of 'other' inputs for 'capital' and 'labour'. Specifically, between 1980 and 2010, the index of the quantity of labour used in Uruguayan agriculture grew from 100 to 113.4, but this longer-term trend masks a significant reduction in labour use during the 1980s and 1990s that was restored only relatively recently; the index of the quantity of capital (including land and machinery) increased from 100 to 107.2 and the index of the quantity of other inputs (including fuel, fertilizers, chemicals, seeds and livestock feed) increased from 100 to 221.5, such that the index of the aggregate quantity of inputs increased from 100 to 130.8, implying that the aggregate quantity of inputs increased at an average annual rate of 0.9 per cent.

The net effect of all these changes was a decrease in the cost share of labour from 27.9 per cent to 26.4 per cent, a decrease in the cost share of capital from 56.3 per cent to 50.5 per cent, and an increase in the cost share of other inputs from 15.8 per cent to 23.1 per cent. The prices of labour and capital both increased by about 150 per cent in nominal terms over the period, whereas the price of other inputs increased by less than 100 per cent. The increase in the cost share of other inputs reflects a relative increase in use that much more than compensates for the relative reduction in price.

4.3. Multifactor productivity

Figure 2 shows the time path of the aggregate index of output, the aggregate index of input, and the ratio of the two, the index of MFP. The index of MFP grew from 100 in 1980 to 186.4 in 2010, equivalent to an average annual growth rate of 2.1 per cent over the 30-year period. But the pattern of growth was uneven, with a significantly lower rate in the decade in the 1990s (1.6 per cent per year) compared with either the 1980s (2.5 per cent per year) and the 2000s (2.2 per cent per year). These results are similar to those obtained by others who have estimated agricultural productivity growth in South America using FAO data. Fuglie (2010) reported an annual growth of productivity for the Southern Cone countries of 2.15 per cent for 1990–1999 and 2.03 per cent for 2000–2007, with a higher annual rate of 2.8 per cent in Brazil for 1975–2007. Bharati and Fulginiti (2007) used a production function approach to measure agricultural productivity growth during 1972–2002 in each of the countries of South America. Brazil had the highest annual agricultural productivity growth rate (2.62 per cent), while Ecuador had the lowest (0.57 per cent) and Uruguay was in-between (1.86 per cent).

5. Modelling agricultural research and productivity

In 2010, Uruguayan agriculture produced 2.44 times the quantity of output produced in 1980, using only 1.31 times the 1980 quantity of aggregate inputs, so MFP approximately doubled. This total growth in MFP reflects varying growth rates in productivity over the 30-year period, which we model as a function of investments in agricultural research and extension, which also evolved over the period of our analysis.

5.1. Model structure

Our model of productivity growth as a function of investments in agricultural research and extension is based on that of Alston *et al.* (2010, 2011), which itself builds on foundations laid by Griliches (1964 and 1979) and Evenson (1967), among others. In our model, agricultural productivity in year t is a function of a stock of agricultural knowledge from public research and extension investments, K_t, a stock of agricultural knowledge from private research,

PR_t, weather, C_t, and random factors, ε_t. Public agricultural knowledge stocks are based on data on total expenditures on public agricultural research and extension over the years 1961–2010, which include research expenditures by CIAAB/INIA and the 'Plan Agropecuario', and a share of total expenditures by the Colleges of Veterinary Medicine and Agriculture of the Public University, which we use as an estimate of their agricultural research expenditures. There are no official data on research expenditures by these two Colleges. Our estimates are based on various reports, such as Beintema *et al.* (2000), Stads *et al.* (2008), and Berreta *et al.* (2010). Reported research spending as a share of total spending varies from 10 to 30 per cent, depending on the source and the time. We know that from the mid-1970s until the mid-1980s, under the military intervention, research funding was minimal, and consequently, we set a 5 per cent share for that period. Then, we allowed for successive increments to reach a maximum of 25 per cent share in the 2000s. BAT (2011, Appendix Table B-1) report the data in full (including details on the research shares of the University budgets).

To transform the data on annual investments into a measure of the knowledge stock, we adopt the gamma lag distribution model used by Alston *et al.* (2010, 2011). Given data limitations, and in view of the relatively applied nature of agricultural R&D in Uruguay, we allow for $L_R = 25$ years, which is longer than allowed in most studies of agricultural R&D. The resulting lag distribution allows for positive contributions to the current stock from up to 25 years of past expenditures on research and extension, but particular values of λ and δ can correspond to a pattern of very low b_k parameters, after a time, that imply a much shorter effective maximum lag.

As a proxy variable to represent the effects of knowledge stocks resulting from private research, PR, we used the number of private cultivars that are included each year in the National Registry; we used the number of varieties of oats, wheat, barley, forage sorghum, corn, sunflower and soybeans. We also included a time-trend variable, to capture the effect of other factors that may have contributed to productivity growth, such as infrastructure improvements, economies of size and scale not associated with innovation or other sources of efficiency gains, technology spillovers from other countries, or private-sector activities not captured by the proxy for private research, PR.

The weather variable (C) was defined as the squared difference between the annual observation of precipitation during September to December and the 30-year average of annual precipitation during September–December (i.e. over the years 1980–2010). We accounted only for precipitation during September–December, because that seems to be the period during the cropping season when precipitation matters most. Low precipitation during those months may result in little water accumulated in the soil, which implies a water deficit for the coming summer crops, and loss of cultivated pastures. Excess of water during that period increases the probability of diseases in winter crops and delays harvest, with negative consequences for yields. It may also delay the sowing of summer crops, which in turn would affect yields because later harvest periods tend to have greater incidence of frost damage. The data used come from the precipitation records of INIA in three of its Experiment Stations. The expected sign of the coefficient would be negative, as a larger value of the variable means that year is either too wet or too dry.

In short, assuming the model is linear in logarithms of the variables, we can express it as

$$\ln MFP_t = \beta_0 + \beta_K \ln K_t + \beta_{PR} \ln PR_t + \beta_T T_t + \beta_c \ln C_t + \varepsilon_t, \qquad (1)$$

where MFP_t is a Fisher ideal index (i.e. a discrete approximation to a Divisia index) of multifactor agricultural productivity in year t; K_t is the stock of knowledge in year t from publicly performed agricultural research and extension over the previous 25 years, in real terms, with lag weights defined using a gamma distribution; PR_t is the stock of knowledge in year t from private agricultural research and extension, proxied by the number of private cultivars that are included each year in the National Registry; T_t is a linear time-trend variable; C_t is a weather index, defined as the squared difference between the annual observation of precipitation during September to December and the 30-year average; and ε_t is a residual, with an i.i.d. structure. Summary statistics are presented in Table 2.

5.2. Estimation results

The models were estimated using STATA 11.2 (StataCorp LP, College Station, TX, USA). Given a maximum lag length of 25 years, and research

Table 2 Simple summary statistics, data for the productivity model, 1985–2010

Symbol	Variable name	Definition	Value description	Value
MFP_t	Multifactor agricultural productivity	Fisher ideal index of agricultural output divided by Fisher ideal index of agricultural output in year t	Minimum Maximum Average	100.0 186.4 138.3
K_t	Stock of public agricultural knowledge	Constructed using 25 years of lagged government spending on agricultural research and extension (in real 2005 pesos) and a gamma lag distribution ($\lambda = 0.70, \delta = 0.90$)	Minimum Maximum Average	165:9 208:5 187:1
PR_t	Stock of private agricultural knowledge	Proxied using the number of cultivars of oats, wheat, barely, forage sorghum, corn, sunflowers and soybeans in the National Registry	Minimum Maximum Average	105 363 188
C_t	Weather	Measured as the squared difference between September to December precipitation and its 30-year average (ie over the years 1980–2010)	Minimum Maximum Average	181.6 91,661.8 18,594.2

spending data beginning in 1961, we were able to fit models to data on MFP for the years 1986–2010. We used a type of grid-search procedure, in which we assigned values for the parameters of the gamma lag distribution (λ and δ), constructed the knowledge stock variables using these parameters along with the expenditures on R&D and then estimated the model using these constructed stocks.[3] By repeating this procedure using different values for λ and δ, we were able to search for the values of these parameters that, jointly with the estimated values for the other parameters, would best fit the data. Combining the following seven possible values for both λ and δ (0.60, 0.65, 0.70, 0.75, 0.80, 0.85, and 0.90) with a fixed maximum lag (25 years) yields a total of 49 possible combinations, which encompass a very wide range of shapes and effective lag lengths (see Alston *et al.* 2010, pp. 280–281).

BAT (2011) report the results from the 49 lag distribution models, in terms of their goodness of fit (measured by sum of squared errors (SSE) and R^2), the elasticity of *MFP* with respect to the public knowledge stock (*K*) and its approximate standard error, and the peak lag (i.e. the length of the lag in years, k, at which the research lag weight, b_k, is greatest, given the values for λ and δ). The best-fitting model was obtained with values for $\lambda = 0.70$ and $\delta = 0.90$, implying a peak lag weight at year 24. This is identical to the best-fitting lag distribution found by Alston *et al.* (2010) for the United States, except that here we have truncated the lag at 25 years, whereas they had an overall lag length of 50 years. Several other models with a similar lag length and shape yielded similar results; but for many of the other models, some of which did not fit the data so well, the implied elasticity of *MFP* with respect to the public knowledge stock is negative, an implausible result. The best-fitting models have plausible values for all of the model parameters, and good statistical properties.

Table 3 summarizes the main results for the highest-ranked four models, arranged in rank order according to goodness-of-fit (SSE) criteria, highest to lowest from left to right. In all four models, the coefficients on the public and private knowledge stock variables, *K* and *PR*, and the time-trend variable, *T*, are statistically significantly different from zero, but the coefficient on the weather variable, *C*, is not. The elasticity of *MFP* with respect to the public knowledge stock is relatively large, at around 0.57 in the preferred specification, compared with previous studies that more often reported elasticities closer to 0.2 or 0.3 (for instance, Alston *et al.* 2010; Sheng *et al.* 2011). The peak lag length at 24 years, while comparable to that of Alston *et al.* (2010) for the United States, is longer than we anticipated for Uruguay given its relatively applied research and extension emphasis.

[3] This approach of estimating productivity models with pre-constructed research knowledge stocks is standard in much of the relevant previous work, but unlike most previous work, and like Alston *et al.* (2010), here we search across the range of possibilities for the lag distribution used to construct that stock, and test among them, rather than simply impose one.

Table 3 Summary of results for the baseline model, four top-ranked models

Model details	Model results			
Model rank by SSE	1	2	3	4
Adjusted R^2	0.908	0.908	0.905	0.903
Lag distribution characteristics				
λ	0.70	0.80	0.90	0.65
δ	0.90	0.85	0.80	0.90
Peak Lag Year	24	24	37	20
Elasticities with respect to				
Public knowledge stock (K)	0.565**	0.724**	0.740**	0.571**
	(0.152)	(0.195)	(0.207)	(0.163)
Private knowledge stock (PR)	0.155**	0.010*	0.145**	0.066
	(0.045)	(0.042)	(0.044)	(0.044)
Weather index (C)	−0.002	−0.004	−0.002	−0.006
	(0.007)	(0.007)	(0.007)	(0.007)
Trend (T)	0.017**	0.018**	0.017**	0.019**
	(0.002)	(0.002)	(0.002)	(0.002)

Notes: Standard errors in parentheses. **Significant at 1%, *significant at 5% and $^+$significant at 10%. SSE is defined as the sum of squared errors. Peak lag is the number of years until the current investment has its maximum impact on the knowledge stock. All explanatory variables enter in natural logarithms.

We tested the models for unit roots using the augmented Dickey–Fuller test, specifically examining the natural logarithms of MFP, private investment and capital stock. We also tested for cointegration using the Johansen test. The results indicated that the data are non-stationary and cointegrated, lending support to the view that the estimates are not spurious because of time-series data problems. We tested for autocorrelation using the Durbin–Watson statistic and comparing this to critical values at the 95 per cent confidence level. While autocorrelation was not a problem in the preferred, baseline model, it was significant in several of the alternatives we tried in examining the sensitivity of findings to specification choices. To correct the estimates in those models that exhibited autocorrelation, we used the Cochrane–Orcutt procedure. Additionally, using the White test, we failed to reject the null hypothesis of homoskedasticity. Detailed results from all of these tests are available in BAT (2011).

5.3. Sensitivity analysis

We tried several alternative specifications with variations in two dimensions. First, we tried alternative assumptions about the fraction of expenditure by the University (Colleges of Agriculture and Veterinary Medicine) to apportion to research. Second, we tried dropping the proxy for the private knowledge stock, *PR*, and the time-trend variable, *T*, or both to see how such omissions would affect the overall performance of the model and the estimated impact of public research.

5.3.1. University budget share

In the baseline model, we applied specific estimates of research spending as a fraction of total spending by the two Colleges, ranging from 5 to 25 per cent in particular years. In the sensitivity analysis, we tried assuming either all or none of the spending by the two Colleges should be counted as contributing to the public agricultural knowledge stock, *K*. Compared with the baseline, the results for the two alternative model structures were less reliable. Treating the entire expenditures for the two Colleges as counting towards public research almost always resulted in implausible, negative estimated elasticities of *MFP* with respect to *K*, and autocorrelation problems. Omitting University expenditures entirely yielded models that were generally similar to those for the baseline model. Detailed results are included in BAT (2011).

5.3.2. Private research roles

Table 4 reports the results for four alternative specifications of the model, with the baseline treatment of University expenditures. The model in column 1 is the baseline model; the model in column 2 omits private research, *PR*, but retains the time trend, *T*; the model in column 3 retains private research but omits the time trend; and the model in column 4 omits both private research and the time trend, *T*. These alternative treatments have interesting implications for the explanatory power of the model, the evidence of autocorrelation in the residuals and the estimated elasticity of *MFP* with respect to the private

Table 4 Summary of results for alternatives to the baseline model

Model details	Model results			
Model rank by SSE	1	2	3	4
Adjusted R^2	0.908	0.896	0.457	0.631
Lag distribution characteristics				
λ	0.70	0.85	0.60	0.60
δ	0.90	0.80	0.60	0.60
Peak lag year	24	24	2	2
Elasticities with respect to				
Public knowledge Stock (*K*)	0.565**	0.910**	0.259**	0.323**
	(0.152)	(0.242)	(0.066)	(0.070)
Private knowledge stock (*PR*)	0.155**		0.120^{+}	
	(0.045)		(0.066)	
Weather index (*C*)	−0.002	−0.008	−0.003	−0.006
	(0.007)	(0.007)	(0.007)	(0.007)
Trend (*T*)	0.017**		0.020**	
	(0.002)		(0.001)	
Durbin–Watson statistic (Original)	2.07	1.72	1.04	0.75
Durbin–Watson statistic (Transformed)	–	–	2.06	1.86

Notes: Standard errors in parentheses. **Significant at 1%, *significant at 5% and $^{+}$significant at 10%. SSE is defined as the sum of squared errors. Peak lag is the number of years until the current investment has its maximum impact on the knowledge stock. All explanatory variables enter in natural logarithms. Models 3 and 4 were corrected for autocorrelation using the Cochrane–Orcutt procedure.

knowledge stock and the lag distribution shape. They indicate some significant correlation between the three variables in question, *K*, *T* and *PR*, as they relate to the dependent variable, *MFP*, such that omitting any or all of them has significant implications for findings with respect to the roles of the others. Knowing what is best to do, and how to interpret the results, can be challenging in such a setting.

Comparing models 1 and 2 (or models 3 and 4), the effect of omitting *PR* is to increase the estimated elasticity of *MFP* with respect to the public agricultural knowledge stock (omitted variables bias from leaving out private research, as suggested by Alston and Pardey 2001 for example, results in an overestimate of the effect of public research on productivity). However, the best-fitting lag distribution shape for the public agricultural knowledge stock, *K*, is not much affected by the omission of *PR*. In contrast, comparing models 1 and 3 (or models 2 and 4), omitting the time-trend variable has a profound effect on the best-fitting lag distribution shape and thus for the public agricultural knowledge stock, *K*, and the estimated elasticity of *MFP* with respect to that stock. In the models that omit the time trend, the best-fitting lag distribution models peak at a lag of two years, an implausibly short lag for anything other than the most applied research and extension. These models also exhibit evidence of significant autocorrelation and much reduced explanatory power, compared with the baseline model. The implied elasticities of *MFP* with respect to the knowledge stock are much smaller, too. In the next section, we explore the implications of these alternative specifications for benefit-cost ratios and estimated rates of return to research.

6. Returns to research

We used the estimated productivity model to compute the *marginal* benefit associated with various hypothetical (counterfactual) changes in research investments. The gross annual research benefits (*GARB*) in year t were computed using the following approximation:

$$GARB_t = \Delta \ln MFP_t V_t \tag{2}$$

where V_t is the real, deflated value (in year 2010 pesos) of agricultural production in year t, and $\Delta \ln MFP_t$ is the proportional change in agricultural productivity in year t, associated with a simulated increase in public agricultural research spending.[4] Because the variables are in logarithms, the simulated proportional change in *MFP* is simply equal to $\Delta \ln MFP = \ln MFP^1 - \ln MFP^0$, where the superscript 0 denotes the predicted ln *MFP* given the actual research expenditure and the 1 denotes the predicted ln *MFP* with the

[4] This approximation is likely to be reasonably valid as a measure of the total benefits for a small research-induced change in production, as a result of a comparatively small change in the research investment.

increased (counterfactual) expenditure. Then, the present value in the year 2010 of accrued benefits (*PVB*) was computed using a (correspondingly real) discount rate of $r = 5$ per cent per year (we also tried values of $r = 3$ per cent per year and $r = 10$ per cent per year, for comparison).

$$PVB = \sum_{t=1961}^{2010} GARB_t \cdot (1+r)^{2010-t} = \sum_{t=1961}^{2010} \Delta \ln MFP_t \cdot V_t \cdot (1+r)^{2010-t} \quad (3)$$

Using our preferred baseline model, we computed $PVB = 163$ million pesos in 2010 for an increase by 1 million pesos in public research spending in 1985. The benefit-cost ratio is given by dividing the present value of the corresponding simulated benefits by the present value of the costs – $PVC = 1$ million times $(1 + r)^{25}$ (=3.4 million pesos for $r = 0.05$). Hence, the marginal benefit-cost ratio is given by $B/C = PVB/PVC = 163/3.4 = 48.2$. We also computed the corresponding conventional internal rate of return and a modified internal rate of return (assuming that flows of benefits would be reinvested at a real interest rate of 5 per cent per annum), following Alston *et al.* (2011). Consider an investment of I_t dollars in time t that will yield a flow of benefits, B_{t+n}, over the following N years. The modified internal rate of return, m, solves the problem:

$$\sum_{n=0}^{N} B_{t+n} (1+r)^{N-n} - I_t(1+m)^N = 0 \quad (4)$$

Intuitively, m is the rate at which one could afford to borrow the amount to be invested, I_t, given that it would generate the flow of benefits, B_{t+n}, which would be reinvested at the external rate, r. Using our preferred, baseline model, we estimated that the modified internal rate of return was 24 per cent per annum for a marginal increase in research spending in 1985. This is somewhat smaller than the conventional internal rate of return, 30 per cent per annum, which itself is lower than many estimates in the literature (e.g. see Alston *et al.* 2000), a result that we ascribe to the comparatively long lag in the present case.

Table 5 reports estimates of the marginal benefit-cost ratio, conventional internal rate of return and modified internal rate of return for a marginal increase in spending in 1985 for our preferred baseline model and the three alternative models that differ in their treatment of the proxy for private research, *PR*, and the time trend, *T*. The conventional internal rate of return is very sensitive to specification choices: In the models that exclude the time trend (models 3 and 4), with their very short lag distribution, the conventional internal rate of return is not well defined; in the models that do include the time trend, it is sensitive to the omission of private research. In contrast, the modified internal rate of return is much more stable across specifications, ranging between 24 and 27 per cent with a reinvestment rate

Table 5 Benefit-cost ratios and internal rates of return

	Model			
	1	2	3	4
Model characteristics				
Peak lag year	24	24	2	2
Elasticity with respect to K	0.565	0.910	0.259	0.323
Discount rate	Benefit-cost ratio			
3% p.a.	71.0	130.6	50.4	62.8
5% p.a.	48.2	90.9	46.4	57.9
10% p.a.	19.3	39.3	38.5	48.0
Reinvestment rate	Modified internal rate of return			
3% p.a.	23.2	26.3	21.4	22.6
5% p.a.	23.7	27.0	23.5	24.6
	Conventional internal rate of return			
	29.7	46.0	620	760

Notes: For each model, the analysis is based on an extra 1 million pesos of R&D expenditures in 1985.

of 5 per cent per year, and varies in an expected fashion as the reinvestment rate is varied. The benefit-cost ratio also varies in a somewhat predictable fashion across specifications. The models that exclude the time trend have a shorter lag (implying a higher benefit-cost ratio) but a much smaller elasticity of MFP with respect to K (implying a larger benefit-cost ratio); the net effect is mixed, depending on the treatment of private research. Leaving out private research increases the estimated benefit-cost ratio for public research by about 25 per cent.

7. Credibility of results

Over the period 1980–2010, our index of MFP increased from 100 in 1980 to about 186 in 2010, and if aggregate input had been held constant at the 1980 quantities, output would have increased by a factor of 1.86:1. Of Uruguay's actual agricultural output in 2010, only 54 per cent (i.e. 100/186 = 0.54) could be accounted for by conventional inputs using 1980 technology, holding productivity constant. The remaining 46 per cent is accounted for by economies of scale along with improvements in infrastructure, inputs and other technological changes. Hence, of the total production value, worth US$4.9 billion in 2010, only 54 per cent or $2.7 billion could be accounted for by conventional inputs using 1980 technology, and the remaining $2.2 billion is attributable to the factors that gave rise to improved productivity. Among these factors is new technology, developed and adopted as a result of public agricultural research and extension.

Figure 3 shows the value of agricultural production, AV_t, in Uruguay over the years 1980 through 2010 partitioned between the part attributable to conventional inputs holding productivity constant, and the residual value, RV_t, attributable to productivity growth since 1980, all expressed in

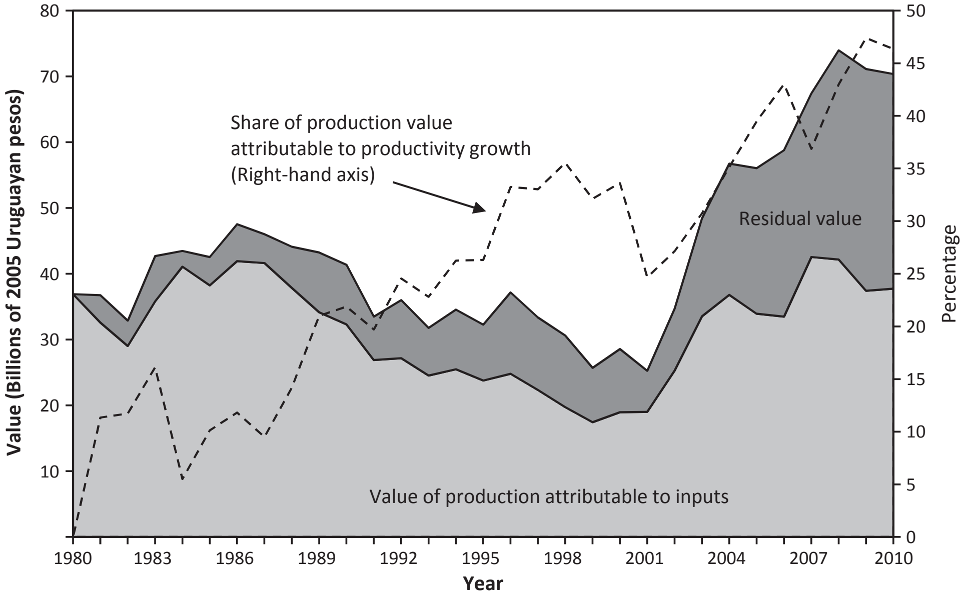

Figure 3 Agricultural output value attributable to productivity growth, 1980–2010.

constant (2005) pesos. The deflated values were compounded at a real interest rate of 5 per cent per annum and evaluated in the year 2010. The resulting stream of values of agricultural output attributable to productivity improvements is equivalent to a one-time payment of more than $31 billion in 2010, an enormous benefit from improved agricultural productivity in Uruguay since 1980.

We compared the value of productivity gains since 1980 compounded forward over 30 years to 2010, against the expenditures on agricultural research and extension, also over 30 years, from 1961–1991, compounded forward to 2010. Both costs and benefits were converted into real terms using the GDP price deflator and accumulated forward to 2010 using various values for the real discount rate. Table 6 reports approximate benefit-cost ratios for a range of assumptions about the attribution of benefits between public research in Uruguay and other sources, about the timing of the flows of benefits and costs to be compared, and about the appropriate rate of discount. Holding other aspects constant, the effect of the attribution rate assumption is direct: the benefit-cost ratio is proportional to the attribution rate. Under the most optimistic scenario (100 per cent attribution) and the most favourable discount rate (3 per cent per annum), the benefit-cost ratio ranges from 24:1 to 55:1, as the period of included costs varies from 40 years, 1961–2001, to 20 years, 1975–1995. This pattern of the effect of changing assumptions about costs is comparable under alternative assumptions about attribution and the discount rate. Varying the discount rate has a very substantial effect on the benefit-cost ratio, and in ways that vary depending on assumptions about the comparable stream of costs. Attributing 50 per cent or more of the

Table 6 Benefit-cost ratios – approximations versus econometric estimates

Period of costs	Discount rate	Share of benefits over 1980–2010 Attributed to public agricultural R&D			
		100%	75%	50%	25%
	Per cent per year	Approximate benefit-cost ratio			
Costs over 1961–2001	3	24	18	12	6
	5	16	12	8	4
	10	6	4	3	1
Costs over 1961–1991	3	31	23	15	8
	5	19	14	9	5
	10	6	5	3	2
Costs over 1965–1995	3	33	25	16	8
	5	22	17	11	6
	10	9	7	4	2
Costs over 1971–1991	3	52	39	26	13
	5	36	27	18	9
	10	16	12	8	4
Costs over 1975–1995	3	55	42	28	14
	5	42	32	21	11
	10	23	17	11	6

benefits over 30 years (1980–2010) to public agricultural R&D in Uruguay over 20 years (1971–1991 or 1975–1995, the last two rows of Table 5) with a 5 per cent per annum discount rate, the approximate benefit-cost ratio ranges from 21:1 to 42:1 – substantially lower but of a comparable magnitude to the econometrics-based estimate of 48:1.

8. Conclusion

Governments around the world are exploring alternative models for financing agricultural R&D, including private–public partnerships whereby commodity levies are used to finance commodity collective goods elements of applied agricultural R&D. The INIA model was partly inspired by and based on the Australian Research and Development Corporation (RDC) model, whereby the government provides dollar-for-dollar matching support for funds raised by commodity levies, and the funds are administered by boards with representatives of industry and the government (e.g. see Productivity Commission, 2011). Australia has some 15 separate RDCs for different commodities (see Productivity Commission 2011) and Uruguay has just one counterpart, INIA which has a much broader mandate. A recent review of the first 20 years of INIA provided the means and opportunity for the present work, which sought to quantify the productivity performance of agriculture in Uruguay and evaluate the contribution of public agricultural research and the INIA initiative to that performance.

INIA was created in a conjunction with other economic policy reforms in Uruguay that served to stimulate the agricultural sector, including forestry, and its effects on the sector are difficult to isolate from the effects of the other policies and influences, as well as other sources of agricultural innovations. While definitive specific conclusions about the role of INIA are not possible, the evidence is broadly favourable. First, agricultural research investments have been revitalized in the post-INIA period, going from a period of essentially flat or declining real spending, and a shrinking share of CIAAB (the precursor to INIA), to a 20-year period of sustained and fairly steady growth in real spending – an almost fourfold increase since 1989, with the lion's share of the growth being in spending by INIA. Second, agricultural productivity growth in Uruguay has been relatively strong over the past 30 years, averaging 2.1 per cent per annum, and has been sustained in the most recent decade of the 2000s. Many countries have experienced a recent slowdown in agricultural productivity. The fact that Uruguay has not experienced a slowdown may be attributable in part, or even significantly, to INIA. However, we do know that other influences were present, such as innovations within farming systems introduced from Argentina.

Third, our econometric analysis attributes a significant portion of multifactor agricultural productivity growth in Uruguay to a public agricultural knowledge stock in a model that includes a measure of private research knowledge (seed varieties) and a time-trend variable to capture the effect of private research and other sources of productivity growth, including international spillovers. This analysis uses a state-of-the-art model, of a type that has previously been applied only in higher-income countries such as the United States (Alston *et al.* 2010) and Australia (Sheng *et al.* 2011) with comparatively extensive data resources available. In the present application, the preferred specification entailed a lag distribution model with a peak lag weight at year 24, a gamma lag distribution with the same shape as found by Alston *et al.* (2010) in their application to a panel of data on 48 U.S. states, but truncated at 25 years rather than 50 years. We expected to find a lag distribution with a much earlier peak for Uruguay, given its comparatively applied research focus. This aspect of our model was sensitive to the inclusion of the other variables that had strong time trends, but none of the specifications we tried resulted in a more-plausible lag distribution model combined other desirable characteristics, and our preferred model statistically dominated the alternatives. As noted by many before us (e.g Griliches 1964, 1979), it may be asking too much of the data to attempt to estimate the structure of the knowledge stock jointly with the other model parameters, especially when we have only a single, short time series of data to work with.

Fourth, the investment appears to have been very profitable. In view of the potential fragility of the econometric estimates, we estimated summary measures of marginal payoffs to research investments based on several alternative specifications as well as our preferred model. The results illustrated that the implied benefit-cost ratios were remarkably similar across four models that had very different specifications of other included variables and thus the lag distribution underlying the public agricultural knowledge stock, and correspondingly different elasticities of productivity with respect to that stock. The preferred model had a benefit-cost ratio of 48:1 computed using a discount rate of 5 per cent per annum, and the three alternative (mis-specified) models had benefit-cost ratios ranging from 46:1 to 90:1. The corresponding measures of the modified internal rate of return were almost identical across all the models, ranging from 23 per cent per annum to 27 per cent per annum with a reinvestment rate of 5 per cent per annum.

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