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Policy, Technology, and Efficiency of Brazilian Agriculture

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A Report from the Economic Research Service

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Policy, Technology, and Efficiency of Brazilian Agriculture

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Abstract

The Brazilian agricultural sector has been transformed from a traditional system of production with low use of modern technologies to a world agricultural leader. That transformation occurred as the country moved away from import-substitution policies—which nurtured domestic industrial development at the expense of agriculture—toward market-oriented policy reforms. These reforms included openness to foreign trade and foreign investment and the use of new technologies, which led to a new growth pattern. To evaluate that transformation, the authors use agricultural censuses spanning 1985-2006 to characterize Brazilian total factor productivity growth, decomposing that growth into technical and efficiency changes. This report presents the findings of a study that focuses on the effect of Brazil's science and technology investments and other public policies on farm production. The findings indicate that agricultural research benefits have been most rapidly adopted by the most efficient farms, widening the productivity gap between these farms and average farms. That gap, however, has been narrowed through other public policies, such as rural credit and infrastructure investments, that favor average producers.

Keywords: Brazilian agriculture, total factor productivity (TFP) growth, technical change, technical efficiency, Embrapa, agricultural research, distance function, stochastic frontier

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What Is the Issue?

Between 1985 and 2006, Brazilian agricultural production grew by 77 percent and Brazil emerged as a major international agricultural exporter. The authors postulate that Brazil's agricultural development was boosted by sustained public investments in science and technology, leading to a stream of new technologies. These investments, in an environment of improving economic liberalization (initiated in the late 1980s) and stability (post-Real plan), may have given farmers incentives to boost farm efficiency and production. However, other policy drivers likely affected farm efficiency, namely, public infrastructure and rural credit investments. To test their hypothesis that science and technology investments were the main impetus to Brazil's agricultural productivity growth, the authors measure Brazil's national total factor productivity (TFP—ratio of total output to total inputs employed in production) and analyze the impact of each of the policy drivers on that productivity growth.

What Did the Study Find?

We hypothesize that Brazil's agricultural development is a result of sustained investments in science and technology that led to a stream of new technologies. These policies, embedded in an environment of macroeconomic stability and economic liberalization, provided farmers with the incentives to boost farm efficiency and production. The study finds:

- That Brazil's national average farm TFP growth increased at an annual rate of 2.55 percent between 1985 and 2006.
- That TFP growth was driven by factor productivity of the most efficient farms, which progressed at an average of 4.4 percent each year. Total factor productivity of the most efficient farms (4.4 percent) is composed of impressive productivity growth in the livestock (7.1 percent annually) and crops (2.9 percent) subsectors.
- The most efficient producers achieved rapid TFP growth, enabling these farms to produce 138 percent more in 2006 than in 1985, while maintaining the earlier input levels.
- The TFP growth of average farms was slower, with mean technical efficiency levels declining from 93 percent in 1985 to 84 percent in 1995/6 and to 64 percent in 2006. These efficiency levels imply that the average farm produced 93 percent of what the most efficient farms produced in 1985, but only 64 percent of what those most efficient farms produced in 2006.
- Despite an enlarging productivity gap between the most efficient and average farms, the average farmer was able to produce 62 percent more in 2006 than in 1985, while maintaining the earlier input levels.
- Public agricultural research—provided through Embrapa, the agricultural research agency linked to the Ministry of Agriculture and Food Supply—appears to have had more influence on the most efficient farms,

widening the TFP gap between those farms and average producers by 0.2 percent for each 1-percent increase in Embrapa's research stock.

- Embrapa's national commodity research centers have been especially important in boosting TFP growth, while its regional resource research centers have not had the same measurable impact. Boosting the national commodity research stock by 1 percent widened the TFP gap by 0.23 percent, while a similar boost to the regional resource stock did not change that TFP gap.
- Of the policies exerting a narrowing influence on the productivity gap between the most efficient and the average producers, rural credit and transportation infrastructure investments have been factors, but primary school infrastructure investments exerted the greatest impact.

How Was the Study Conducted?

To analyze Brazil's TFP growth, the authors use decennial Brazilian farm census data obtained from the Brazilian Institute of Geography and Statistics (IBGE). These data are combined with data from Avila and Evenson (1995), Barros (1999), Brazil's agricultural research agency, Embrapa, and Brazilian statistical yearbook information. The authors use these data, controlling for a number of factors, to evaluate Brazil's national agricultural productivity growth and analyze policy impacts on productive efficiency. The analysis entails estimating a stochastic distance frontier, which makes it possible to distinguish technical change among Brazil's principal commodity groups. The method further allows estimation of the TFP growth of both the most efficient farms and the average farms and of the TFP gap separating them. Technical efficiency statistics are estimated for each microregion and year and are used in evaluating the effects of Government policy on Brazilian farm productivity.

Introduction

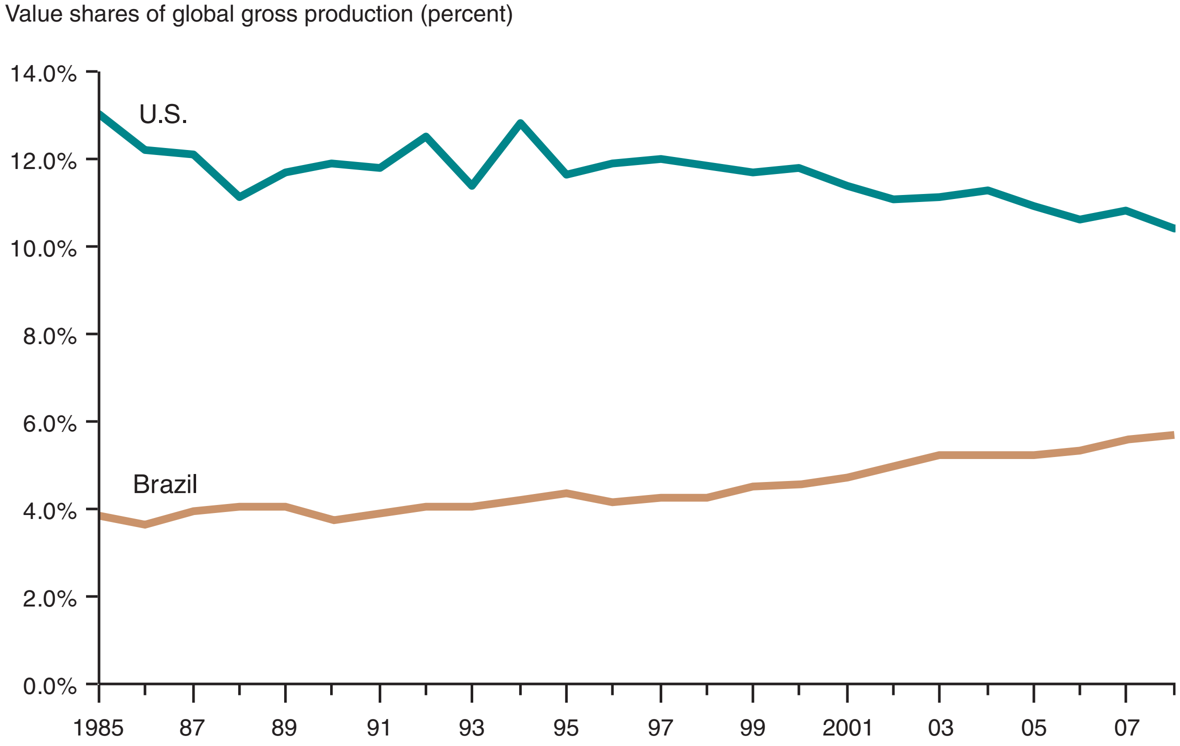
Brazil is viewed by many as the latest exemplar for global agriculture, based on its agricultural growth, strong trade performance, and untapped potential. With the world's largest arable land area of 76 million hectares (IBGE, 2010), fifth largest population base (FAO, 2011), and strong record of agricultural production and exports, the attention focused on the country is not surprising. Economic reforms in the 1980s and early 1990s and agricultural technologies designed for tropical soil conditions have led to greater exploitation of Brazil's considerable land availability, enabling the country to discover its agricultural potential.

Over the last quarter-century, Brazil's agricultural production has grown significantly. Using production and trade data from the Food and Agriculture Organization of the United Nations (FAO), we find that the total value of the country's agricultural production between 1985 and 2008 grew 3.79 percent each year, driving up its share of total global production from 3.9 percent in 1985 to 5.7 percent in 2008. To provide context, that value-share growth is placed in contrast to that of the United States (fig. 1). The robust production growth has increased Brazil's agricultural exports, with the total value of its agricultural trade growing 7.70 percent annually between 1985 and 2008.

While crops, especially soybeans, have been the focal point of many reports on the increasing importance of Brazilian agriculture in global markets

Figure 1

Narrowing the agricultural production value-share gap between the United States and Brazil, 1985-2008



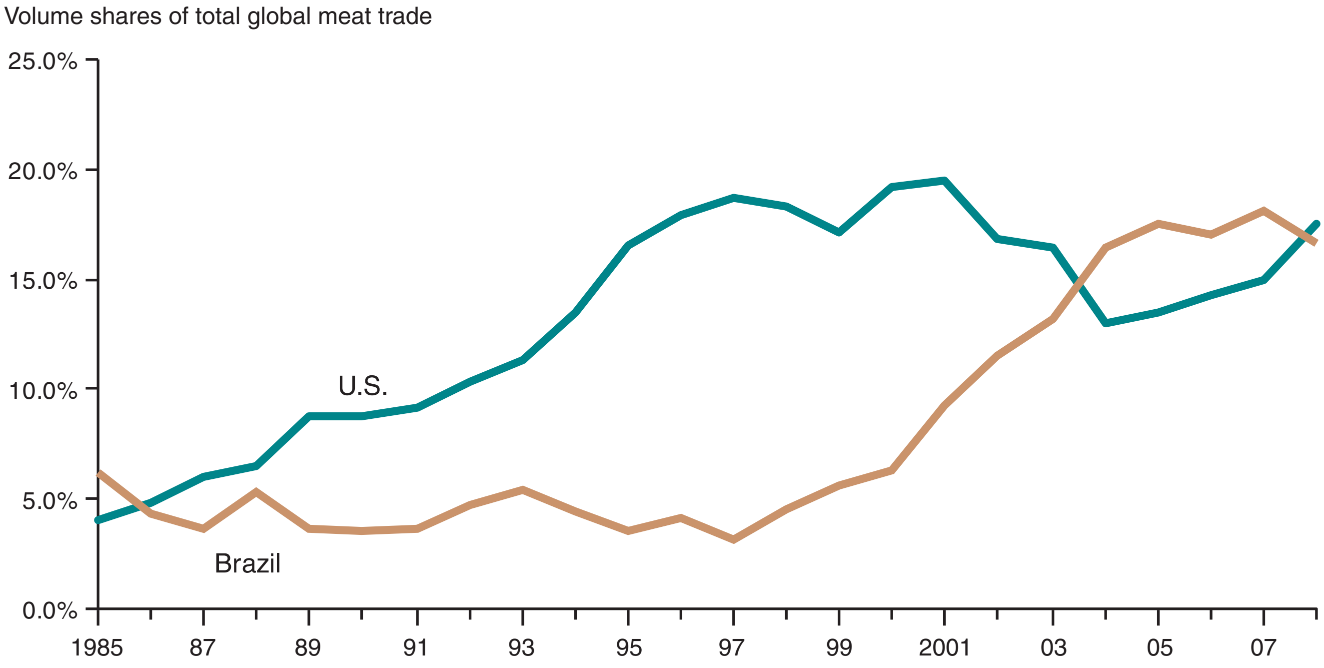
Source: Food and Agriculture Organization *FAOSTAT Agricultural Databases*. Available at: http://faostat.fao.org/.

(Schnepf et al., 2001; Constantin et al., 2009; *The Economist*, 2010), one of the country's most rapid gains in global trade has been in the livestock subsector. In light of the World Trade Organization's Uruguay Round, which further liberalized meat trade in international markets, Brazilian livestock producers between 1985 and 2008 experienced an increase in their share of total volume of meat traded by 9.70 percent annually. That growth rate accelerated after 2000 by 17.42 percent each year until 2008. As depicted by figure 2, although the United States and Brazil were trading in separate global beef markets due to restrictions caused by the endemic presence of foot-and-mouth disease (FMD) in Brazil, by 2008, Brazil had caught up with the United States' 17.6-percent share of the global meat trade. (U.S. beef exports did incur restrictions over the 2004-07 period due to bovine spongiform encephalopathy (BSE)).

We hypothesize that Brazil's agricultural development is a result of sustained investments in science and technology that led to a stream of new technologies. These policies, embedded in an environment of macroeconomic stability and economic liberalization, provided farmers with the incentives to boost farm efficiency and production. We test our hypothesis by measuring Brazil's national total factor productivity (TFP) growth using the three consecutive decennial farm censuses (1985, 1995/6, and 2006) conducted since its return to democracy in 1985. TFP, defined as total output per total measureable inputs, measures the efficiency of production. We then examine Brazilian policies affecting farm efficiency—namely, agricultural research, public infrastructure, and rural credit investments.

Brazil has the potential to greatly expand its crop area, but maintaining its position as a top global supplier of agricultural products is likely to depend

Figure 2
Rise in Brazil's share of total global meat trade, 1985-2008



Source: Food and Agriculture Organization, *FAOSTAT Agricultural Databases*. Available at: http://faostat.fao.org/.

more on continued advances in efficiency. Our results indicate that was the case between 1985 and 2006, as productivity among the most efficient producers rapidly improved, particularly in the livestock subsector.[1] Average farms were, however, unable to keep pace with the most efficient farms defining the best-practice frontier. We further find that agricultural research has widened the TFP gap between best-practice and average farms, while public infrastructure and credit investments have narrowed that gap.

[1] The study's level of observation is the microregion. We refer to farms or producers rather than microregions, however, when evaluating results. Aggregated, microregion-level data allow for imputations to farms, an imputation that is wrong only to the extent that the data suffer aggregation problems. Because of this, we refer often to farms to more clearly communicate the story to policymakers, the intended audience.

Policy Review

In the post-World War II period, Brazil sought to establish an independent domestic industrial base through import substitution industrialization (ISI) policies that replaced imported inputs with domestic production. The ISI policies placed direct and indirect pressure on agriculture, shaping its performance. For example, export quotas, licenses, and taxes were accompanied by import controls on farm inputs, thereby raising fertilizer, chemical, and machinery prices above international prices (Schnepf et al., 2001). Agriculture benefited from these policies to the extent that the industrial base provided domestically produced agricultural inputs to modernize the sector, but the import and export controls explicitly and implicitly taxed farmers, lowering the returns to technology investment. The National System of Rural Credit was established in 1965 to promote agricultural modernization by quickening capital formation and increasing foreign exchange earnings (Schnepf et al., 2001).

Agricultural export growth flourished in the 1970s, with soybeans holding a central position, and mini-devaluations and offsetting subsidies helped to reduce the implicit agricultural taxation caused by ISI policies (Graham, Gauthier, and Barros, 1987). But by 1979, an oil-price shock, rising international interest rates, and Mexican debt repayment problems propelled Brazil's managed economy toward its own fiscal crisis. Policies affecting its agricultural performance and macroeconomic environment were at times contradictory. For instance, Helfand and Rezende (2004) note that the expansion of agricultural support price programs in the 1980s was intended to stimulate production and increase foreign exchange earnings in Brazil, but rural credit contractions obstructed that goal. Indeed, it appears that Brazil's management of the macroenvironment led to a long transition period from ISI policies to the liberalized ones that eventually improved agriculture's investment and production environment and expanded the private sector's role.

That transition period included a return of elected officials in 1985 who considered a variety of stabilization plans to deal with Brazil's unstable macroeconomy.[2] Various consecutive plans were aimed at harnessing inflation through price stabilization, deregulation, fiscal tightening (tax increases, Government spending reductions), privatization, and removal of nontariff trade barriers and licensing. To boost competitiveness, Brazil joined the Southern Common Market (Mercosul) in 1991, which eliminated tariffs on most Argentinean and Uruguayan imports.

Brazil's last stabilization effort, the 1994 *Real* plan, introduced market-oriented reforms—including a reduction in the State's role of setting prices, managing production, and regulating the trade of wheat, coffee, sugar, and milk—and decreased industrial protection that further contributed to agricultural modernization, particularly in the pork, poultry, and dairy sectors (Helfand and Rezende, 2004). The *Real* plan coincided with the development of grass-fed cattle production as a low-cost activity, allowing farmers to withstand rising input prices, tight credit conditions, and export taxes more easily than they could with crop production. During this stabilization effort, commercial hog and poultry production was initiated in Brazil's Center-West

[2] For a more comprehensive review of Brazil's macroeconomic policy reforms, see Graham, Gauthier, and Barros (1987), Schnepf et al., (2001), and Helfand and Rezende (2004).

region—sponsored by major international companies and targeted almost exclusively at international markets.

The World Bank's nominal rates of assistance to agriculture, which represent price distortions induced by policy interventions, indicate that the post-*Real* plan period was the first time Brazilian agricultural producers experienced sustained net subsidization rather than taxation (Anderson et al., 2008). This change in economic policy was likely an incentive for private investments in agricultural technology and efficiency improvements, with private investors taking advantage of Brazil's public investment in agricultural research and increased credit availability. Agricultural research plays the greatest role in raising productivity through technical innovations, while credit provides a primary means of accessing those new technologies.

Agricultural Research

Despite a proliferation of Brazilian research institutes and experiment stations in the first half of the 1900s, it was not until the 1960s that national agricultural modernization became a priority. Indeed, apart from São Paulo State's research efforts on exportables coffee and cotton, agricultural research was largely underfinanced and poorly managed, and investment in human capital and rural extension services was deficient (Graham et al., 1987). Following a comprehensive review of the agricultural research system, Embrapa (Brazilian Enterprise for Agricultural Research) was created in 1973 as a national agricultural research agency, organized along Federal lines and involving cooperation between Federal and State experiment stations. The agency employs a decentralized model of applied research, split between national commodity, regional resource, and "thematic" centers that allow for both a national and local focus (app. table C2).

Initially, Embrapa was tasked with providing extension services for the distribution of technological packages, including new seeds, soil correction techniques, and improved production practices. Embrapa's most notable achievement, however, has been the development of technologies allowing agricultural expansion to the acidic soils of the Cerrado biome (fig. 3). The Cerrado ecosystem is a savannah; its topography, climate, and soil characteristics have been conducive to large cattle-raising operations and have favored mechanized and technologically intensive cultivation of soybeans, corn, cotton, and sugarcane. The infertile and acidic soils of the Cerrado were originally used for extensive cattle production systems in the 1960s. Embrapa's development in the 1970s of more productive perennial grasses—such as adaptation of the African *Brachiaria* species, which has a high nutritional value, provides greater nitrogen fixation and requires less phosphorus fertilization than native pastures—provided a significant technological breakthrough in creating pastureland. This led to more intensive farming systems as cattle ranchers replaced extensive production schemes in pastures of low productivity with beef and milk production, resulting in increased livestock productivity and farmer income. Later, Embrapa expanded its efforts to developing high-yielding and disease-resistant crop varieties; seed for rice, beans, wheat, and potatoes; and more improved grass varieties to support new livestock breeding programs.

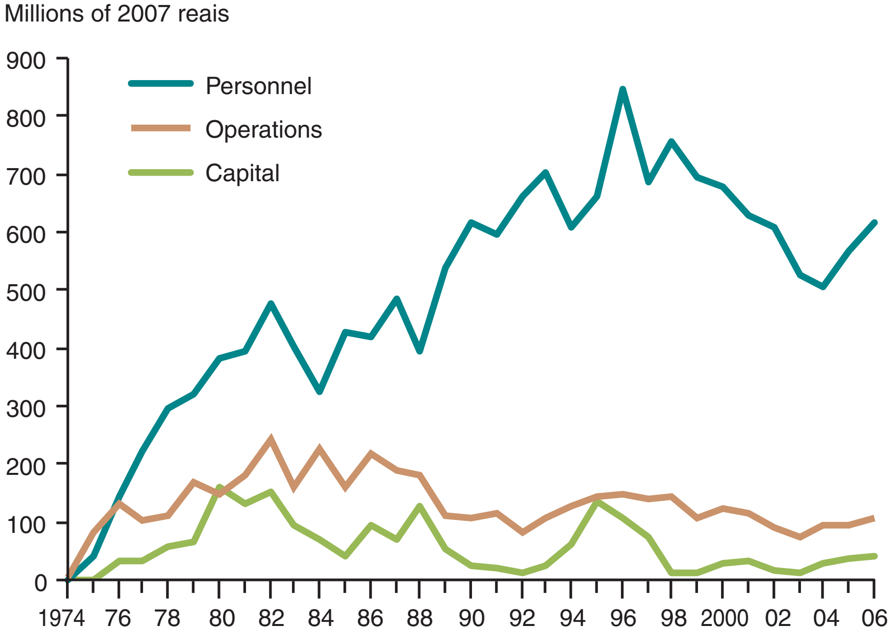
Figure 3
Brazilian States and biomes

Source: Brazilian Institute of Geography and Statistics (IBGE), 2006.

Embrapa is financed principally through Federal funds. The proportion of Government support rose from 78 percent in 1986 to 91 percent in 1999 and was maintained at that high level through 2006 (Beintema et al., 2001; Stads and Beintema, 2009). Those funds have been allocated largely to personnel expenses (fig. 4). Over our sample period (1985-2006), the share of total Embrapa expenditures allocated to personnel increased from 68 to 80 percent (table 1). Within the Embrapa research structure, personnel expenditures have been allocated primarily to the national commodity and regional resource centers, but their combined shares fell from 84 percent in 1985 to 76 percent in 2006 (table 2). Thematic research accounts for the remaining research expenditures, with its share growing over each decade.

Regional resource research differs from national commodity research in that it centers on technologies specific to States, biomes, and climates rather than on commodities with a national scope. Thematic research primarily supports national commodity and regional resource work in areas such as basic seed production, soil conservation, and genetics and biotechnology. These research centers, however, do not operate in isolation. For example, the more productive *Brachiaria* perennial grass was a joint development effort by international research centers, Embrapa's Cerrado and West regional research centers, and Embrapa's beef cattle national commodity research center.

Figure 4
Embrapa expenditure allocations, 1974-2006



Source: Embrapa (Brazilian Enterprise for Agricultural Research), 2010.

Table 1
Embrapa expenditure allocations, 1985-2006

Year	Personnel	Capital	Operations
		Percent	
1985	68	6	26
1995	70	15	15
2006	80	6	14

Source: Embrapa (Brazilian Enterprise for Agricultural Research), 2010.

Table 2
Embrapa expenditure allocations on research center personnel, 1985-2006

Year	National commodity	Regional resource	Thematic
		Percent	
1985	38	46	16
1995	34	44	22
2006	33	43	24

Source: Embrapa (Brazilian Enterprise for Agricultural Research), 2010.

By 2006, Brazil's agricultural research intensity—that is, its research expenditure per dollar of agricultural gross domestic product (GDP)—had fallen from Latin America's highest to second highest. Research intensity declined despite higher Government spending on research and research staff than in any other Latin American nation during the census periods we examined (Stads and Beintema, 2009). In 2006, Embrapa accounted for 57 percent of spending on public agricultural research institutions. However, Government support for research increased during 2007–09, no doubt helping Brazil reemerge as Latin America's leading public research entity (Beintema et al*.,* 2010).

Rural Credit

The National System of Rural Credit was created in 1965 to quicken capital formation in exportable farm products (Schnepf et al., 2001). The 1970s were a period of rapid rural credit growth—the most important lever for raising shortrun farm output at the time—which exacerbated inflationary pressures (Graham et al., 1987). Graham and colleagues note that the proportion of rural credit to agricultural GDP rose from 58 percent in 1971 to a peak of 94 percent in 1976 and subsequently fell to 43 percent in 1981. By the 1990s, credit was funneled primarily to small farmers, leaving commercial producers to seek private credit sources. Rural credit volume declined throughout the 1980s and early 1990s, with reductions in the 1980s caused by international donor community pressure and in the 1990s through implementation of the various stabilization plans (Helfand and Rezende, 2004; Schnepf et al., 2001).

Rural credit includes credit for investing in, producing, and marketing commodities. Government-subsidized rural credit represents about a third of the total credit needs of the agricultural sector in Brazil. The private sector (private banks, input providers, brokers, and farmers) provides the rest, a change from pre-1994 reforms when the Brazilian Government provided the bulk of the credit needs.

Agricultural credit has been directed toward financing crop and livestock production, as well as capital investments in agricultural infrastructure and equipment. Capital investments have included machinery for planting and harvesting and for the processing of livestock products and pastureland expansion. Over three-quarters of the investment credit disbursed between 1985 and 2006 has been issued to the livestock sector, boosting livestock's credit investments by 4.7 percent annually, more than double the investment credit allocations for crops during the same period (BACEN, 2009). The livestock sector's greater growth in investment credit indicates Brazil's priority of modernizing livestock production.

Evaluating Productivity Growth

Total factor productivity (TFP) is generally defined as an accounting measure, taken as the ratio of an aggregate of total outputs to an aggregate of total inputs and measuring the efficiency with which inputs are transformed into outputs. TFP is preferable to other partial-productivity measures, such as yield per hectare (land productivity) or output per worker (labor productivity), because those partial measures account for only a single factor of production, whereas TFP accounts for the contributions of all measurable inputs, such as land, labor, capital, and materials.

While TFP accounting measures have the benefit of providing statistics for each sample year, they are ratios that do not account for random—or stochastic—processes, nor do they permit the decomposition of TFP into technology and efficiency changes, options that are available with some econometric or linear programming approaches. Modeling TFP in a stochastic framework is important because agriculture is inherently random, a phenomenon captured with an econometric error. Technical change is defined here as TFP growth of the most efficient producers who form the technical frontier. Technical efficiency change is a measure of the difference between TFP growth of the most efficient producers and that of average producers (average-farm TFP) and is referred to as the TFP gap.[3]

Total Factor Productivity Measurement

One econometric method of measuring TFP is with a production function in which aggregate output is statistically correlated with measurable inputs. Shifts in the production function represent shifts in supply, and because a production function evaluates data at their mean, the function's shifts represent *average-farm* TFP growth. An alternative measure is based on a production "frontier" that establishes the statistical relationship between inputs and outputs for the most efficient—or frontier—producers. Thus, a shift in a production frontier represents TFP of the most efficient farms.

In light of Brazil's recent substantial agricultural production growth, particularly in the livestock subsector (fig. 2), we employ the stochastic distance frontier method to measure Brazil's total factor productivity growth (see box, "Productivity Definitions"). The distance portion implies modeling more than one aggregate output grouping. The frontier component allows TFP growth measurement of the most efficient farms and average farms, as well as of the TFP gap separating them. This stochastic distance frontier approach is important because it provides information on the roles of different subsectors and farms in productivity growth that can assist policymakers.

Technical change is measured by the model's time trend, allowing us to distinguish statistically technical change among multiple output groupings (app. B). But because the time trend provides just one parameter estimate over the entire sample period, only an annual average technical change rate is obtainable for each subsector. Technical efficiency levels, however, are estimated by the model for each period. These information constraints imply that the annual average-farm TFP growth estimate is also only available as an average estimate for the entire 1985-2006 sample period because it is defined

[3] To the extent that scale economies are present in Brazilian agriculture, the total factor productivity growth estimates capture that impact.

Productivity Definitions

Accounting Measures

Total Factor Productivity (TFP): Ratio of an aggregate output to an aggregate input

Land Productivity (Yield per hectare): Ratio of an aggregate output to total land

Labor Productivity (Output per worker):Ratio of an aggregate output to total laborers

Stochastic Econometric Measures

Production function:An approach that correlates output variations with input variations, **all data evaluated at their averages**. Productivity growth is measured as the expansion of output (or shifts in the function over time), holding all inputs constant at their mean levels.

Production frontier: An approach that correlates output variations with input variations, **all data evaluated relative to the best-practice (most efficient) producers defining the technical frontier**. Technical change is measured as the expansion of output (or shifts in the frontier over time), holding all inputs constant at their mean levels.

Distance function: An econometric approach that is similar to a production function but that **allows for more than a single output**. A distance function may be specified as an output distance function, measuring the growth in output from a mean set of inputs, or as an input distance function, measuring the reductions in inputs given a set level of output.

Distance frontier: Combining the definitions of a production frontier and a distance function, a distance frontier **allows for more than a single output, and all data are evaluated relative to the best-practice (most efficient) producers who define the technical frontier**.

Technical change: TFP growth of the most efficient producers.

Technical efficiency change: Difference of TFP growth between the most efficient and average farms, also referred to here as the TFP gap.

Average-farm TFP growth: Technical change plus technical efficiency change.

as the summation of the aggregate technical change rate and the change in the mean technical efficiency levels between censuses.

Assessing Total Factor Productivity

In its present application to Brazilian agriculture, technical change is estimated in the crop and livestock subsectors using a stochastic distance frontier (app. B, equation B.8) and Brazil's decennial agricultural census data (1985, 1995/6, and 2006). Technical change statistics for the crop and livestock subsectors are computed following the method provided in Rada et al. (2011). This method entails successively differentiating parameter estimates presented in appendix D with respect to each output group and the time trend and then applying the implicit function theorem. Once obtaining the technical change estimates of the two subsectors (crops, livestock), we weight them by their respective mean revenue shares to obtain one aggregate (all-agriculture) technical change statistic. Summing the all-agriculture technical change statistic with the change in mean technical efficiency—obtained from equation B.9 in appendix B—provides Brazil's average-farm TFP growth rate. (See appendix A for a diagrammatic and more technical understanding of measuring TFP by way of a stochastic distance frontier, and appendix B for the technical methodology employed.)

After obtaining the average-farm TFP growth rate, decomposed into its technical change and technical efficiency change components, we use the technical efficiency levels to examine the impact of three public policy categories:

(1) Public agricultural technology investment, represented by research stocks;

(2) Public infrastructure investment, represented by road density, primary school education, and landline telephone connections; and

(3) Credit investment, represented by rural credit volumes.

Agricultural research plays the strongest role in raising farm productivity. Roads are the primary conduit for supplying and accessing markets and are associated with economic development in middle-income and lower income nations (Calderón and Servén, 2004). Credit provides the liquidity for obtaining and modernizing farm inputs. Primary schools improve farmers' human capital, enhancing their ability to employ new techniques and technologies, and telephones are important for transmitting information.

Data

Critical to any productivity study is the quality of data employed. The farm-level survey data collected in the Brazilian agricultural censuses are employed at two aggregation levels, microregion and State.[4] Metric tons of each output commodity, hectares of agricultural land, and expenditures for fertilizer, feed, seed, pesticides, livestock vaccines, and electricity are all available in the census at the microregion level. In these data, we captured 558 microregions distributed across the 27 States, each contributing directly to the cross-sectional variation we seek to exploit in our statistical analysis. Some data covering labor, livestock, and farm machinery are available at the microregion level; the remaining data are State aggregations. The policy data, recorded in the annual statistical yearbooks or obtained from Embrapa, are available at the State level or, in the case of agricultural research expenditures, at the level of the decentralized research unit (app. table C2). All data not available at the microregion level were imputed to the microregion, enabling their use in our microregion-level efficiency evaluation. Each of Brazil's 27 States is displayed in figure 3. Technical details of each variable's construction are provided in appendix C, and sources of agricultural production and policy data are provided in appendix table C1.

[4] Microregions are Brazilian political subdivisions encompassing several municipalities, or counties, and there are various microregions in each State.

The strength of the Brazilian agricultural census data lies in the stability of its structure across census years, with data on 20 outputs and 11 inputs for the 558 microregions repeated across the 1985, 1995/6, and 2006 census years. Of the 20 commodities included in table 3, crops accounted for 72 percent of total revenue in 1985, with livestock making up the other 28 percent. By 2006, the livestock sector had gained 6 percentage points, shifting the crop and livestock shares to 66 and 34 percent, respectively. Recorded inputs consist of agricultural land, labor, farm machinery, livestock, fertilizer, feed, seed, pesticide, animal vaccine, and electricity.

Production Inputs

We converted agricultural labor counts, recorded in the censuses as either family or hired labor, to male-labor equivalents. Each has declined over the three census periods (fig. 5). Between 1985 and 2006, hired labor counts declined by 26 percent, as did family labor, which is noteworthy given how many more family laborers exist in Brazilian agriculture than hired laborers and implies a substantially greater absolute decline in family laborers. In 1985, family labor accounted for 16.7 million laborers and hired labor for 4.8

Table 3

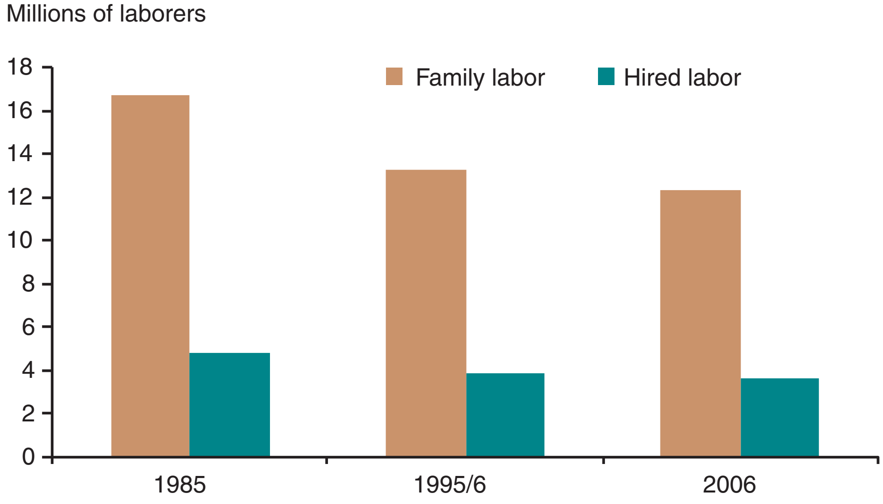
Commodity coverage of Brazilian agricultural total factor productivity growth analysis, 1985-2006

Crops	Beans, cotton, maize, manioc, onion, groundnuts, rice, soybeans, wheat, tomato, bananas, cocoa, coffee, oranges, and sugarcane
Livestock	Cattle meat, eggs, cow milk, poultry meat, and pig meat

Source: IBGE. (Instituto Brasileiro de Geografia e Estatística), 2010: Rio de Janeiro. Available at: http://ibge.gov.br/.

Figure 5

Decline in hired and family male-equivalent laborers, 1985-2006



Source: Authors' estimates using data from IBGE (Instituto Brasileiro de Geografia e Estatística), 2010: Rio de Janeiro. Available at: http://ibge.gov.br/.

million. By 2006, family labor had fallen to 12.4 million laborers and hired labor to 3.6 million. The Brazilian agricultural sector has shed a significant portion of its labor over the previous 20 years, reflecting a rural-to-urban migration acceleration following the 1994 stabilization program and echoing agricultural productivity's contribution to the overall economic development process (discussed by Johnston and Mellor, 1961).

Land

The agricultural census data provide hectares of land that are quality-differentiated into four groups: permanent cropland, temporary cropland, natural pasture, and planted pasture. Permanent croplands are those planted to perennials, and temporary croplands are planted to annuals, forages, and flowers. Natural pastures may be partly cultivated; planted pasture may be degraded or improved.

Aggregate land in production, assembled by simple summation across each land group, fell 6 percent between 1985 and 2006, from 241.7 million hectares to 226.8 million hectares. However, this aggregate summation masks shifts across the different land groups, as the majority of Brazil's agricultural land (74 percent) is in pastures. Upon careful examination, we note that pastures indeed skew the aggregate land story. As natural pastures fell by 38 percent, new planted pastures rose by 37 percent between 1985 and 2006. This presumed substitution of planted for natural pastures is consistent with greater applications of perennial grasses. There also has been a 17-percent expansion of permanent cropland and a 9-percent contraction of temporary cropland.

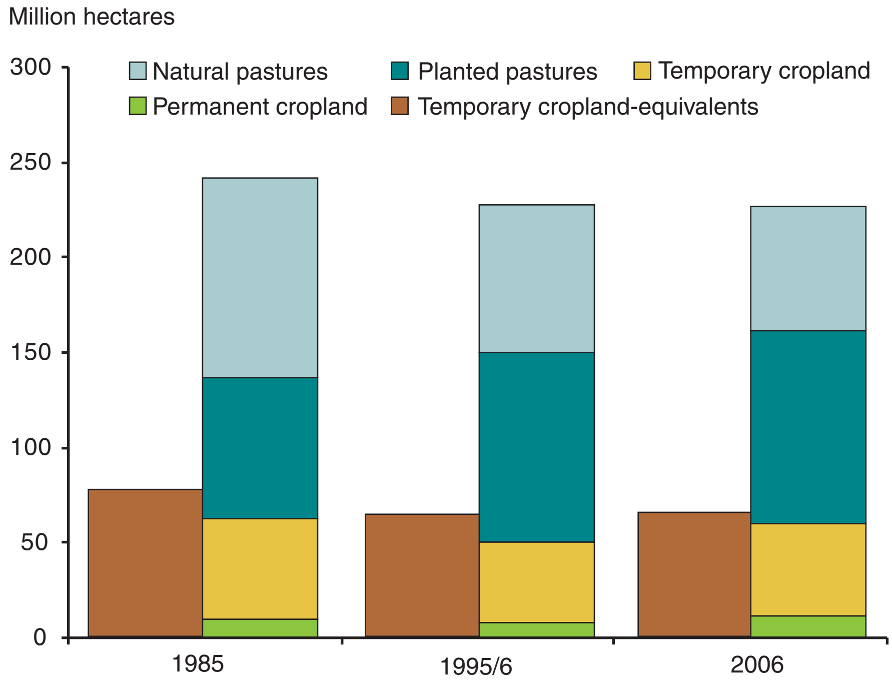
In the present approach to measuring productivity growth, each land group was aggregated into a single aggregate land variable. Land quality-adjustment is important for measuring productivity growth because bias might arise if land changes occur unevenly among land groups (Fuglie, 2008), as was the case in Brazil (fig. 6). Lacking rental rates for each land group—price information that would account for uneven changes—we formed a temporary cropland-equivalent series by estimating land weights for each land group and for each census period, following the method described in Fuglie (2010). The aggregate land series is nearly 3.5 times as large as the temporary cropland-equivalent series; the adjusted land series fell from 76.8 million hectares in 1985 to 65.2 million hectares in 2006, or 15 percent over the two decades (fig. 7).

Capital and Materials

Annual farm service expenditures on capital (including tractors and livestock) and materials (including fertilizer, seed, pesticide, animal vaccine, feed, and electricity) were computed for each census year. Data deficiencies in the 1985 census year bar the inclusion of other machinery capital. Material expenditures increased over the 1985-2006 period by 19 percent, while capital expenditures declined by 28 percent. Most growth in material expenditures occurred between 1995/6 and 2006 (table 4). Material growth was in fact negative for nearly all items except for electricity consumption, which showed extraordinary growth over the 1985-1995/6 period. Capital service expenditures for machinery and livestock declined across each census year, despite stocks of machinery (tractors) rising 23 percent and livestock rising

Figure 6

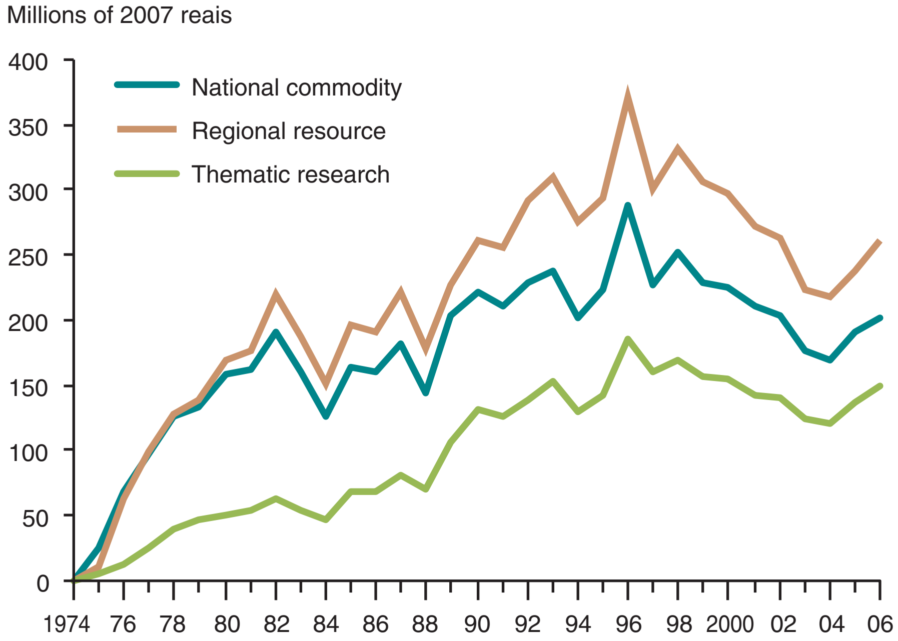
Comparison of raw and temporary cropland-equivalent land changes, 1985-2006



Source: IBGE (Instituto Brasileiro de Geografia e Estatística), 2010: Rio de Janeiro. Available at: http://ibge.gov.br/., and author's estimates.

Figure 7

Embrapa's national commodity, regional resource, and thematic personnel expenditures, 1974-2006



Source: Embrapa (Brazilian Enterprise for Agricultural Research), 2010.

Table 4

Change in material expenditures, 1985-2006

Census period	Fertilizer	Seed	Pesticide	Animal vaccine	Feed	Electricity	Total
				Percent			
1985-2006	38.7	-56.1	119.6	-16.2	-44.0	486.3	18.6
1985-1995/6	-47.8	-49.0	-32.7	-41.2	-87.5	784.5	-73.0
1995/6-2006	165.9	-13.9	226.1	42.5	348.5	-33.7	339.5

Note: Expenditures are in real 2006 reais. Source: Authors' estimates.

Table 5

Change in capital service expenditures and stocks, 1985-2006

	Capital expenditures		
Census period	Machinery	Livestock	Total
		Percent	
1985-2006	-5.7	-56.7	-28.3
1985-1995/6	-4.9	-51.1	-25.5
1995/6-2006	-0.7	-11.3	-3.8
	Capital stocks		
	Machinery	Livestock	Total
		Percent	
1985-2006	23.0	25.9	NA
1985-1995/6	20.5	17.8	NA
1995/6-2006	2.1	6.9	NA

Note: Expenditures are in real 2006 reais.
NA = Not applicable.
Source: Authors' estimates.

26 percent between 1985 and 2006 (table 5). These growth estimates suggest a constriction of material expenditures between the first two census periods and considerable expansion between the last two periods. The estimates also suggest that while capital service expenditures declined, machinery and livestock stocks increased, suggesting improved capital longevity.

Agricultural Research

Following Huffman and Evenson (1993), Embrapa's personnel expenditures were used to estimate agricultural research knowledge stocks.[5] Research stocks are preferred to using expenditures directly to account for research's productivity impact because an expenditure series assumes each year's expenditures affect productivity in that year only. However, any one year's expenditures will generate knowledge and technologies that will benefit future production. Research stocks represent agricultural research investments over multiple years, capturing research's time-varying impacts.

[5] Embrapa is employed in the analysis as a proxy for Brazil's public agricultural research. And while Embrapa is the dominant public agricultural research institution in Brazil, it is not the only institution conducting research. For a review of Brazilian agricultural research institutions and funding, the reader is referred to Beintema et al. (2010), Stads and Beintema (2009), and Beintema et al. (2001).

National commodity and thematic centers conduct research on specific commodities or themes that may have applications for all producers in Brazil, and each microregion in Brazil was assumed to benefit from the technologies developed by these two kinds of research centers. Regional resource research, however, is constrained to specific States, biomes, or climates (app. table C2). Thus, the benefits from regional resource research are not national but are tailored to local conditions. Therefore, we assumed that the regional resource centers with a State focus develop technologies specific to the needs of that State's producers. For regional resource centers that develop technologies related to specific biomes or climates, we employed geographic information systems (GIS) to determine which producers are assumed to benefit from those specifically designed technologies.

By using personnel expenditures to account for the impact of agricultural research on productivity (fig. 4), we found that, within those expenditures, regional resource research has received the greatest proportion of total funding (fig. 7). Given that these research centers sometimes collaborate, we accounted first for the impact of Embrapa's total personnel expenditures on farm efficiency and then for the separate impacts of national commodity, regional resource, and thematic research. This approach gives a combined impact of all Embrapa research centers on productivity and then attributes the impact of each of the three types of research.

Rural Credit Investments

The credit variable, which accounts for production, investment, and marketing farm credit, is measured in terms of value per contract and is lagged 1 year to account for its potentially noninstantaneous impact. The credit measure increased by 104 percent in real terms between 1984 and 1994, rising from 37,000 reais per contract in 1984 to 77,200 reais per contract in 1994 (fig. 8).[6] This value rose because credit volume declined at a greater rate than did the total value of credit. This trend was reversed by 2005 as the number of contracts increased by 294 percent and the total value of all contracts rose by 25 percent, lowering the value per contract to 13,200 reais. The reversal in total value per contract indicates that credit was dispersed in greater quantities and at lower values, confirming credit's increasing dispersion to a greater number of farms.

Infrastructure Investments

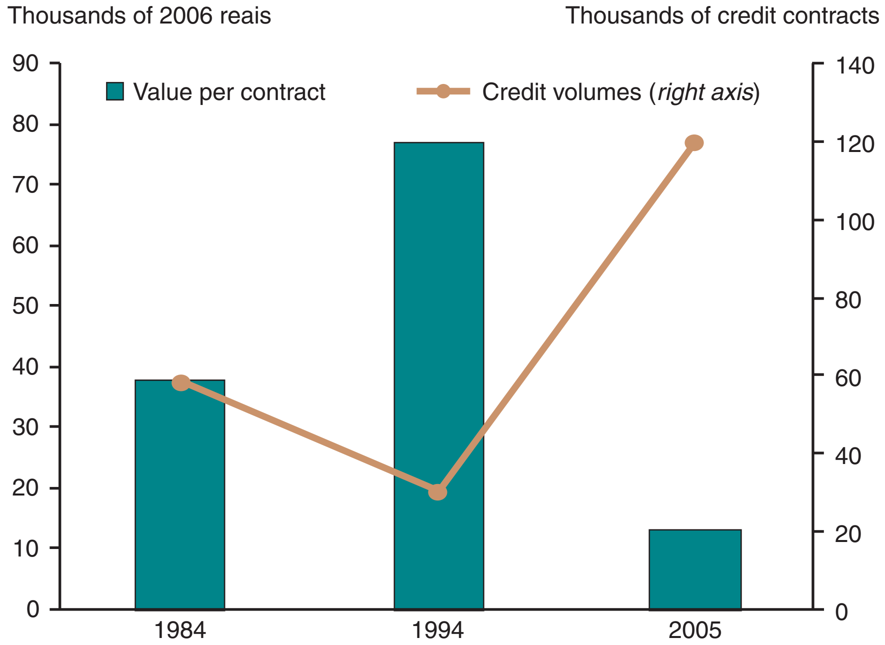
Three infrastructure investments were included in the analysis to assess their impact on productivity: (1) paved road density, (2) schools per 1,000 inhabitants, and (3) total landline telephones. Road density is defined as the sum of the length in kilometers (km) of asphalt road divided by land area (km^2). In 1985, Brazil's paved road density measured 0.008, rising to 0.017 in 1995 and to 0.021 by 2006. By 1985, Brazil had constructed 69,105 km of roads amid its 8.5 million square hectares of total land area. By 2006, total paved roads had risen to 179,264 km, indicating that between 1985 and 1995, paved roads increased by 113 percent but then grew only 21 percent in the following decade.

School infrastructure, proxied by the number of primary schools per 1,000 persons, declined across each of the census years, falling on average from

[6] Credit data are presented in constant 2006 reais.

Figure 8

Fluctuating distribution of rural credit, 1984-2005



Source: Brazilian annual statistical yearbooks, various editions. Anuário Estatístico do Brasil. IBGE (Instituto Brasileiro de Geografia e Estatística), Rio de Janeiro, Brazil.

1.72 primary schools per 1,000 inhabitants in 1985 to 1.63 in 1995 and 1.10 in 2006. Total school establishments fell by 30 percent between the initial 2 census years, but recovered by 21 percent in 2006. Brazil's population, which rose by 37.7 percent over the 1985-2006 period, led to the declining trend in the school infrastructure measure. The number of telephone lines in service expanded rapidly, rising from 7 million connections in 1985 to 14.8 million in 1995 and to 38.8 million landlines in 2006. However, the use of cell phones—information not recorded in the 1985 or 1995/96 censuses—likely dampens the total impact telephone communication may have because cell phones are often substitutes for landline connections.

Results

Table 6 gives the estimated impact of each policy driver on every microregion's technical efficiency level. The technical change (TFP of the most efficient farms), technical efficiency change (TFP gap separating most efficient from average farms), and TFP growth estimates for average farms are shown in table 7. Table 8 provides Brazil's average-farm efficiency levels relative to the most efficient farms for each census year. Because of the differing personnel expenditures allocated by Embrapa to each of the three research centers (fig. 7) and our interest in attributing Embrapa's aggregate impact, we assess the effect of the aggregate Embrapa research stock and each research center's stock separately. In doing so, however, we find a very high correlation (0.99) between the national commodity and thematic research center stocks. We therefore omit the thematic center research stocks from the analysis given

Table 6

Policy impacts on productive efficiency, 1985-2006

Dependent variable: Technical efficiency	Estimated coefficients	
	Percent	
	Specification 1	Specification 2
Total Embrapa research	-0.20***	
National commodity research		-0.23***
Regional resource research		0.00***
Paved roads	0.08***	0.08***
Rural credit	0.07***	0.07***
Schooling	0.11***	0.11***
Landline telephones	0.00	0.00
Constant	3.15***	3.57***
Adjusted R2	0.40	0.39
N	1,617	1,617

*** = Statistical significance at the 1-percent level.
Source: Authors' estimates.

Table 7

Annual technical change, technical efficiency change, and TFP growth rates, 1985-2006

Item	Annual change
	Percent
Crop technical change	2.93
Livestock technical change	7.13
All-agriculture technical change	4.44
Technical efficiency change	-1.89
Average-farm TFP growth rate	2.55

Source: Authors' estimates.

Table 8

National technical efficiency, 1985-2006

Year	National technical efficiency
1985	0.93
1995/6	0.84
2006	0.64

Note: Number of observations=539 for each year.
Source: Authors' estimates.

the center's role in supporting national commodity and regional resource research in areas such as soil conservation and biotechnology.

Policy Impacts on Productive Efficiency

To determine the impact of Brazil's science and technology policy on its production efficiency, we analyzed how a 1-percent increase in each policy variable impacts Brazil's technical efficiency or TFP gap (table 6). Our findings indicate that research had a negative impact and rural credit and infrastructure investments had a positive impact on productive efficiency. The findings suggest that research has widened the TFP gap between average farms and the most efficient ones that comprise the technical frontier, whereas rural credit and infrastructure investments have narrowed that gap. A 1-percent increase in the total Embrapa research stock pushes the TFP growth rate of the most efficient farms 0.20 percent further ahead of the average farm. Thus, while research likely boosts the productivity of all farms**,** Embrapa's research appears focused toward—or has been primarily adopted by—the most efficient farms.

We find that a 1-percent increase in the national commodity research stock enlarges the TFP gap by 0.23 percent (table 6). An equivalent increase in the regional resource research stock does not expand or narrow that gap. These estimates suggest a limited impact of the regional resource research that may require further investigation, particularly in light of the greater personnel funding to these centers (table 2 and fig. 7). One possible explanation may be that the regional resource centers conduct predominately maintenance research (Plunket and Smith, 1986; Marasas, Smale, and Singh, 2003). Because regional resource research has not shifted the average farm closer to or further from the best-practice frontier established by the most efficient farms, these centers may be conducting—among other things—research that adapts innovations from the national commodity centers to each regional resource's research, focusing and sustaining the impact of those innovations despite changes in the production environment.

Alternatively, the results consistently show that investments in roads, education, and rural credit tend to improve average-farm efficiency and narrow the TFP gap (table 6). Of the policies evaluated, education exerts the largest positive impact, shifting the average farm toward the best-practice frontier. A 1-percent increase in the roads, rural credit, and schools per capita variables improves mean efficiency relative to the frontier by 0.08, 0.07, and 0.11 percent, respectively. That education has the largest impact is noteworthy, particularly given that the overall education variable has not risen over time. The result is more understandable if we interpret it in terms of the sample's broad cross-section; that is, those areas with more schools per 1,000 inhabitants experienced greater average farm efficiency. Landline telephones had a very small and insignificant impact on technical efficiency.

Technical Change, Technical Efficiency Change, and TFP Growth

The technical change estimates show remarkable growth, particularly for the livestock subsector (table 7). Between 1985 and 2006, TFP of the most efficient farms reached a strong 2.9 percent annual growth rate in crops and a formidable 7.1 percent growth rate in livestock. Weighting each subsector's technical change by its respective revenue share, we obtain an all-agriculture annual technical change of 4.4 percent, which means that the most efficient producers in 2006 were able to produce 138 percent more than in 1985 without increasing input usage.

This high growth rate, however, was not achieved by all producers, as technical efficiency declined by 1.9 percent each year. That is, between 1985 and 2006, TFP growth of the most efficient producers accelerated each year at a rate 1.9 percent faster than that of the average farm, annually widening the TFP gap between the two by nearly 2 percent. The average farm's efficiency levels relative to the most efficient producers are presented in table 8 for each census year. The change in efficiency levels or expanding TFP gap, combined with the all-agriculture annual technical change rate of 4.4 percent, equals the all-agriculture annual average-farm TFP growth estimate of 2.55 percent between 1985 and 2006 (table 7).[7] This estimate is close to Gasques et al.'s (2010) index-number finding of 2.87 percent over the same period. Brazil's average-farm TFP growth rate indicates that average farms in 2006 were able to produce 62 percent more than in 1985 with constant input levels.

[7] The productivity estimates reflect decennially recorded production data. When providing the results, we assume linear growth over each decade; that is, total factor productivity improved 25.5 percent each decade between 1985 and 2006. To allow comparisons with other productivity studies, the result is generalized to 2.55 percent.

Conclusion

Brazil's production growth has been driven by an increase in agricultural efficiency, as evidenced by strong technical and TFP change over the 1985–2006 period. Different types of research investments have different effects on agricultural production in Brazil. The significantly greater impact from Embrapa's national commodity research than from its regional resource research may be a cause for concern among Brazilian policymakers. One proposed explanation of the differing impacts is that the regional resource research centers focus on maintenance research while the national commodity research centers aim at innovation and the development of new agricultural technologies. These results suggest that Embrapa's national commodity research programs are the ones most effective at boosting technological growth, providing the driving force behind Embrapa's agricultural research success.

Sustained investments in science and technology policies, supported by a stable, liberalized macroeconomic environment, have helped Brazil achieve significant agricultural gains. Brazil could substantially boost its shares in global production and trade still further by raising its low 2006 average-farm efficiency; that is, average farms produced only 64 percent of what the most efficient producers achieved in 2006. The results suggest that new school infrastructure investments provide the largest boost to average-farm efficiency, likely through raising human capital, which, in turn, contributes to a farmer's ability to employ and manage new agricultural technologies and practices. Thus, despite its remarkable gains, Brazil has ample capacity for further productivity improvements.

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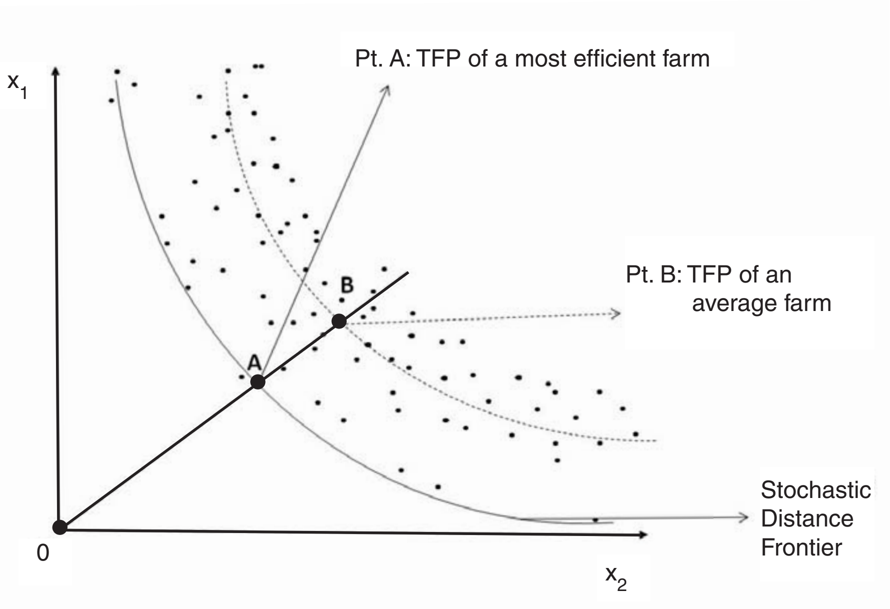
Appendix A. Understanding Total Factor Productivity (TFP) from a Stochastic Input Distance Frontier

Appendix figure 1

Understanding TFP from a Stochastic Input Distance Frontier



Source: Authors' construction.

Stochastic distance frontiers are unique in that they allow productivity to be measured for more than one output *and* by defining the frontier as the most efficient farms. We are thus able to determine *how much more efficient* one farm is relative to the next. The figure above provides an example of a stochastic distance frontier at which, along the given ray, point A employs the fewest inputs needed to produce mean output *y*. Because TFP may be defined as an aggregate of total outputs per aggregate of total inputs, or $\frac{y}{x}$, TFP at frontier point A then is $FP_A = \frac{y}{\overrightarrow{OA}}$, namely, mean output divided by inputs x_1 and x_2 represented in distance $\overrightarrow{OA}$. Efficiency of the average farm, point B, produces the same output at higher input levels. Thus, we can write average-farm TFP as $FP_B = \frac{y}{\overrightarrow{OB}}$, or mean output divided by distance $\overrightarrow{OB}$. Technical efficiency , TE, is the ratio of TFP at the average (FP_B) and frontier (FP_A) farm: $TE = \frac{FP_B}{FP_A} = \frac{\overrightarrow{OA}}{\overrightarrow{OB}}$. Solving for FP_B and taking logs gives $\ln FP_B = \ln FP_A + \ln TE$. In proportional terms, that is, TFP of the average farm is the sum of frontier TFP (or TFP of most efficient farms) and mean technical efficiency (or the average distance from the average farm to the frontier).

Appendix B. Estimation Method

Our strategy is to characterize agricultural technology by way of its input requirement set $L(y^o_{jit}) = \{x_{kit} \in \mathbb{R}^K_+ : (y^o_{jit},\, x_{kit},\, t) \in T\}$, that is, the inputs x_{kit} and technology T necessary to produce output set y^o_{jit}, in which $y^o_{jit} \in \mathbb{R}^M_+$, $j = 1 \ldots M$ are scalar outputs; $x_{kit} \in \mathbb{R}^K_+$, $k = 1 \ldots K$ are scalar inputs; $t = 1 \ldots S$ are technology indicators; and $i = 1 \ldots N$ are the observations on technology $T = \{(x_{kit},\, y_{jit},\, t) : x_{kit} \text{ can produce } y_{jit}\} \in \mathbb{R}^{K+M}_+$.

Our deterministic input distance function

(B.1) $$D_I\,(x_{kit}\,,\, y_{jit}\,,\, t) = \sup_\lambda\{\lambda > 0 : x_{kit}/\lambda \in L(y^o_{jit},\, t)\}\ \forall\, y_{jit} \in \mathbb{R}^M_+$$

is dual to input set $L(y^o_{jit}\,,\, t)$ and hence technology *T*. In particular, if inputs are weakly disposable, equation (B.1) implies $D_I(\cdot) \geq 1$ if and only if $x_{kit} \in L(y^o_{jit}\,,\, t)$. When $D_I(\cdot) = 1$, λ obtains its minimum at unity, and inputs x_{kit} are located on the boundary of the input requirement set, maximizing technical efficiency. Yet, stochastic frontiers differ from their deterministic counterparts in that maximized technical efficiency is not constrained to unity. Central to releasing this restraint is the composite error term (Aigner, Lovell, and Schmidt, 1977; Meeusen and Van den Broeck, 1977):

(B.2) $$D_I(x_{kit},\, y_{jit},\, t;\, \boldsymbol{\beta}) = e^{v_{it} - u_{it}}$$

in which $\boldsymbol{\beta}$ is a parameter vector to be estimated; $u_{it} \sim N^+(\mu,\, \sigma^2)$ is a nonnegative, truncated normal error representing an observation's distance from the frontier; and v_{it} is an independently and identically distributed (iid) random noise with mean zero and variance σ^2_v. Error terms v_{it} and u_{it} are assumed to be distributed independently of one another: $\sigma_{vu} = 0$.

Specifying the left-hand side of (B.2) as

(B.3) $$D_I(x_{kit},\, y_{jit},\, t;\, \beta) = e^{F(\ln x_{kit},\ \ln y_{jit},\, t;\, \beta)}$$

substituting it into (B.2), and employing Battese and Coelli's (1992) time-effect parameterization of inefficiency error u_{it}—that is,

$U_{it} = U_i \eta_{it} = U_i \exp[-\eta(t - S_i)]$; η being an iid random variable to be estimated—allows a stochastic technical-efficiency (*TE)* interpretation:

(B.4) $$D_{it} = e^{F(\ln x_{kit},\ \ln y_{jit},\ t;\ \boldsymbol{\beta})} \Big/ e^{v_{it}} = TE_{it} = e^{-u_i \exp\left[-\eta(t-S_i)\right]}.$$

To impose linear homogeneity on (B.4), that is, $D_I(\cdot) = \omega D_I(\cdot)$ for any $\omega > 0$ (Shephard 1970), we let $x^*_{kit} = x_{kit} / x_{lit} \neq +\infty$, where the l^{th} input is chosen as numeraire (Lovell et al., 1994). Rearranging terms in equation (B.4) and substituting $1/x_{lit}$ for ω brings

(B.5) $$e^{F(\ln y_{jit},\ \ln x^*_{kit},\ t\ ;\ \beta)} = 1/x_{lit} \cdot e^{F(\ln y_{jit},\ \ln x_{kit},\ t\ ;\ \beta)}$$
$$= \frac{e^{v_{it} - u_i \exp\left[-\eta(t-S_i)\right]}}{x_{lit}}.$$

Taking logs of (B.5) and rearranging terms gives:

(B.6) $$-\ln x_{lit} = F(\ln y_{jit},\ \ln x^*_{kit},\ t;\ \boldsymbol{\beta}) - v_{it} + u_i \exp\left[-\eta\left(t - S_i\right)\right].$$

We express the Brazilian agricultural input distance frontier $F(\ln y_{jit},\ \ln x^*_{kit},\ t;\ \boldsymbol{\beta})$ as a generalized Cobb-Douglas,

(B.7) $$F(\ln y_{kit},\ \ln x^*_{kit},\ t;\ \boldsymbol{\beta}) = \beta_0 + \sum_{j=1}^{M} \beta_j \ln y_{jit} + \sum_{k=1}^{K-1} \beta_k \ln x^*_{kit} + \beta_t t.$$

Output subscript *j* indexes crops and livestock, and input subscript *k* indexes land, family labor, hired labor, and capital and materials; *i* indexes 558 Brazilian microregions, and *t* indexes the time trend (1985, 1995/6, 2006). Land is used as the numeraire input to facilitate parameter estimate interpretation.

Rewriting the Cobb-Douglas terms, inclusive of State dummies $M_h,\ h = 1,\ldots,H,$ on the right side of (B.7) as $F(M_h,\ \ln y_{jit},\ \ln x^*_{kit},\ t;\ \boldsymbol{\beta})$ and substituting into (B.6) gives

(B.8) $$-\ln x_{lit} = F(M_h,\ \ln y_{jit},\ \ln x^*_{kit},\ t;\ \beta) - v_{it} + u_i \exp\left[-\eta\left(t - S_i\right)\right].$$

Statistically differentiating technical progress among the multiple outputs requires successively differentiating appendix D's distance frontier estimates with respect to the three product outputs and the time trend and then applying the implicit function theorem (Rada, Buccola, and Fuglie, 2011). Equation B.8 was estimated using Stata 11.2, command *xtfrontier,* and the time-varying decay (tvd) inefficiency error specification. Estimating technology frontier (B.8) also provides observation-specific mean technical efficiency levels:

(B.9) $$E\left[TE_{it}\right] = E\left[e^{-u_i \exp\left[-\eta(t-S_i)\right]}\right].$$

Efficiency levels are then logged and regressed against Government research stocks R_{it}, road density D_{it}, one-period lagged rural credit $C_{i,t-1}$, education E_{it}, and landline phones L_{it},

$$\ln TE_{it} = g\left(\ln R_{it},\ \ln D_{it},\ \ln C_{i,t-1},\ \ln E_{it},\ \ln L_{it};\ \delta\right) + \varepsilon_{it}, \tag{B.10}$$

where δ is a vector of estimable parameters, and ε_{it} is a normally distributed idiosyncratic error term with mean zero and variance σ_{ε}^{2}.

Appendix C. Data

As described below, some of the inputs are quantity indexes and others are expenditure indexes. Upon converting all output and input prices to reais, we normalize 1985 and 1995/6 prices to a 2006 basis via Brazil's General Price Index-Domestic Availability (IGP-DI), which captures wholesale, consumer, and construction price changes (IBRE, 2010).

Labor

Labor inputs in the 1985 and 1995/6 periods are from Avila and Evenson (1995) and are available at the State level. 2006 labor data are available at the microregion level (IBGE, 2010). Two male-equivalent labor quantity indexes were constructed, representing hired and family labor. Proportionate female-to-male average 1998-2002 International Labor Organization wage rates, specific to Brazilian agriculture, were used to quality-adjust female labor to male-labor equivalents (ILO, 2010). Female agricultural labor wages were, on average, 92 percent of male wages over that period.

Labor counts in the 1985 and 1995/6 data were distributed across type (family, permanent-hired, and temporary-hired labor) and agricultural subsector (crop, livestock, and forestry labor). We followed Avila and Evenson (1995) and interpolated crop-labor quantities to the microregion by weighting every labor type in the crop subsector by each microregion's State share of cropland. Interpolating livestock-labor counts follows a similar approach, but the weight applied was each microregion's State revenue share of livestock sold. Forestry labor weights were assumed equal for every microregion in each State.[10]

Our hired labor variable was formed by summing permanent and temporary labor counts. Both hired and family labor were multiplied by each State's agricultural labor gender share to obtain the proportion of male and female laborers in that State. All labor data were then reaggregated into male-equivalent quantity indexes using the International Labor Organization wage data. The 2006 census labor counts are available by gender and labor type at the microregion level and also were converted here to male-equivalent family and hired labor quantity indexes.

Land

Land size is available in the censuses at the microregion level and quality-differentiated into four groups: permanent cropland, temporary cropland, natural pasture, and planted pasture. Permanent croplands are those planted to perennials, and temporary croplands are those planted to annuals, forages, and flowers. Natural pastures may be partly cultivated; planted pasture may be degraded or improved. Because adding 1 acre of natural pastures would likely have substantially less importance than adding 1 acre of temporary cropland that is regularly managed, we form a temporary cropland-equivalent quantity series. To obtain temporary cropland-equivalent land quantities, we used Fuglie's (2010) method to estimate land weights for each land group and census period. Quality-adjusting land is important for measuring productivity growth because bias might arise if land changes occur unevenly among land groups (Fuglie, 2008).

Capital and Materials

We formed a service expenditure index from capital and material inputs. The capital service index, due to a shortage of recorded data in the 1985 census, includes only tractors. State-level tractor service prices are from Barros (1999). Barros estimates 1985 and 1995/6 tractor service prices by using new and used 1997-98 prices of two Massey Fergusson tractor sizes, amortized over 21 years at a 7-percent depreciation rate and, after converting 1985 prices to reais, deflating them by the IGP-DI to a 2006 basis. Census data on numbers of total tractors in use were then multiplied by the service prices. The 2006 service expenditures were obtained by multiplying 1995/6 service prices by the IGP-DI, allowing a projection to 2006, then multiplying by tractors-in-use.

Livestock capital accounts for on-farm stocks of bulls and steer, cattle, horses, asses, mules, pigs, goats, chickens, roosters, and hens. These stocks are available at the State level in 1985 and 1995/6, at the microregion level in 2006, and were aggregated to ‘bovine equivalents’ using cattle-normalized weights from Hayami and Ruttan (1985, p. 450). State bovine-equivalent animal stocks were imputed to each microregion by multiplying each State’s stock by every microregion’s State share of livestock sold. Bovine sale prices are available by State in 1985 and by microregion in 1995/6 and 2006. Those prices were amortized over 10 years at a 10-percent discount rate to obtain a bovine-equivalent capital service price. Multiplying the bovine-equivalent animal stocks by the service price provided the livestock capital service rate.

Materials include fertilizer, seed, pesticide, animal vaccine, feed, and electricity expenditures. These data are available at the microregion level for each census period. As with all other input data, 1985 expenditures are converted to reais, then the IGP-DI is employed to deflate 1985 and 1995 expenditures to a 2006 basis.

Agricultural Technology Investments

Despite Embrapa’s creation in 1973, research expenditures (PE_{it}) were not allocated to Embrapa personnel until 1975. Because the first census sample period is 1985, we had a very short time lag in creating our research stock (R_{it}). Accounting for this short lag we—like Evenson and Alves (1998)—did not construct a depreciation component into the research-stock lag structure, but, rather, assumed a geometric lag structure in which we had a 1-year lag before research expenditures began; then research’s productivity impacts started 10 years before the present and rose geometrically:

$$\text{(C.1)}\qquad R_{it} = 0.000978 * PE_{i,t-1} + 0.001955 * PE_{i,t-2} + 0.00391 * PE_{i,t-3}$$

$$+0.00782 * PE_{i,t-4} + 0.01564 * PE_{i,t-5} + 0.03128 * PE_{i,t-6}$$
$$+0.06256 * PE_{i,t-7} + 0.12512 * PE_{i,t-8} + 0.25024 * PE_{i,t-9}$$
$$+0.50048 * PE_{i,t-10}.$$

Equation (C.1) states that our research stock in time t and for microregion i is a weighted sum of the previous 10 years' expenditures, with weights rising geometrically, placing greater emphasis on the later years. Because the national commodity and thematic centers conduct research on specific commodities or themes that may be applied by all producers across the entire nation, we assigned to each microregion the national commodity and thematic research expenditures. Regional-resource research, however, was constrained to specific States, biomes, or climates (app. table C2). For those centers with a State focus, we assigned the research expenditures to each microregion in that State's geographic boundary. With respect to those centers focusing on specific biomes or climates, we used a unique approach of employing geographic information systems (GIS) in assigning each center's research expenditures to every microregion in which the centroid of that observation lies within the biome or climate in question. Microregion-level research expenditures, accounting for national commodity, regional resource, and thematic research, were then summed, and equation (C.1) was used to compute each microregion's aggregate Embrapa research stock.

Rural Credit Investments

Rural credit is recorded in the annual statistical yearbooks by total value and contract numbers. A total credit value per contract variable was constructed from rural credit information to avoid any bias that may be introduced by employing strictly values or contract counts. Credit values per contract were lagged by 1 year under the assumption that credit does not impact production instantaneously. Between 1995/6 and 2006, a change in the level of aggregation occurred in which rural credit was recorded, with State-level data available in the former period but only national-level information available in the latter. For the 1985 and 1995/6 census periods, a State's microregions were each assigned that State's credit per contract volumes; in the 2006 contract period, every microregion was assigned the national total per contract volume.

Infrastructure Investments

State-level road densities were measured as total kilometers of paved roads, expressed as a proportion of the State's geographic area (km^2) and assigned equally to each micro-region in that State. State-level school infrastructure was proxied by the number of primary schools per 1,000 persons and assigned equally to each microregion. Telecommunication was proxied by the number of landline telephones in service, and the data are available at the State level. Each microregion in every State was assigned the State values.

Appendix table C1
Data sources

Series	*Level of aggregation*	*Source*
Commodity production	Microregion	IBGE
Agricultural land use	Microregion	IBGE
Persons employed primarily in agriculture	State & Microregion	Avila and Evenson (1995) & IBGE
Tractors in use	Microregion	IBGE
Livestock capital	Microregion	IBGE
Fertilizer expenditures	Microregion	IBGE
Farm-level commodity prices	Microregion	IBGE
Tractor service prices	State	Barros (1999)
Farm animal prices	State & microregion	IBGE
R&D expenditures	Decentralized unit	Embrapa
Total primary schools per capita	State	Annual Statistical Yearbooks[a]
Road density (km/area)	State	Annual Statistical Yearbooks[b]
Rural credit	State	Annual Statistical Yearbooks[c]

SIBGE is the Brazilian Institute of Geography and Statistics.

[a] 1987 – 88, 1997, and 2007 Statistical Yearbooks.

[b] 1985, 1986, 1990, 1995, 1997, 2006, and 2008 Statistical Yearbooks.

[c] 1987 – 88, 1992, 1997, and 2007 Statistical Yearbooks.

Appendix table C2

Embrapa Research Centers

Embrapa Centers	*Decentralized Units*		*Unit Focus*
National Commodity Centers	CNPSO	Embrapa Soy	National
	CNPA	Embrapa Cotton	National
	CNPGL	Embrapa Dairy Cattle	National
	CNPGC	Embrapa Beef Cattle	National
	CNPMF	Embrapa Manioc and Fruit	National
	CNPMS	Embrapa Corn and Sorghum	National
	CNPSA	Embrapa Pig and Poultry	National
	CNPAF	Embrapa Rice and Beans	National
	CNPH	Embrapa Horticulture	National
	CNPT	Embrapa Wheat	National
Regional Resource Centers	CPAMN[a]	Embrapa Middle-North	Piauí and Maranhão
	CPATSA	Embrapa Tropical Semi-Arid	Caatinga biome
	CPATC	Embrapa Coastal Tablelands	Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergípe, and Bahia
	CPAP	Embrapa Pantanal (Marshlands)	Pantanal biome
	CPACT[b]	Embrapa Temperate Climate	Temperate climate
	CPAO[c]	Embrapa West	Paraná, Mato Grosso do Sul, Mato Grosso
	CPAC	Embrapa Cerrado (Savannah)	Cerrado biome
	CPPSE	Embrapa Southeast Livestock	Minas Gerais, Espírito Santo, Rio de Janeiro, and São Paulo
	CPPSUL	Embrapa South Livestock	Paraná, Santa Catarina, Rio Grande do Sul
	CPAF-AC	Embrapa Acre	Acre
	CPAF-RO	Embrapa Rondônia	Rondônia
	CPAF-RR	Embrapa Roraima	Roraima
	CPAF-AP	Embrapa Amapá	Amapá
	CPAA	Embrapa Western Amazon	Amazonas
	CPATU	Embrapa Eastern Amazon	Pará

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Appendix table C2

Embrapa Research Centers—continued

Embrapa Centers	*Decentralized Units*		*Unit Focus*
Thematic Centers	CNPS[d]	Embrapa Soils	National
	CNPAB	Embrapa Agro-biology	National
	CNPMA	Embrapa Environmental	National
	CENARGEN	Embrapa Genetic Resources and Biotechnology	National
	TechTransfer[e]	Embrapa Technology Transfer	National
	CNPDIA	Embrapa Agricultural Instrumentation	National
	CNPM	Embrapa Satellite Monitoring	National
	CNPTIA	Embrapa Agricultural Information	National
	CTAA	Embrapa Agro-industrial Food Technology	National
	CNPAT	Embrapa Tropical Agro-industry	National

[a] CPAMN expenditures include UEPAE Teresina expenditures from 1974 to 1992.

[b] CPACT expenditures include CNPFT and CPATB expenditures from 1974 to 1992.

[c] CPAO expenditures include Uep-MT expenditures.

[d] CNPS expenditures include Uep Recife expenditures.

[e] TechTransfer expenditures include SNT and SCT expenditures.

Source: Embrapa (Brazilian Enterprise for Agricultural Research), 2010.

Appendix table D

Technology Parameter Estimates

Dependent Variable: Land	Coefficients	Standard Error	Z	P>|Z|
Time trend	0.041	0.002	19.58	0
Livestock	-0.058	0.010	-5.86	0
Crops	-0.141	0.007	-19.92	0
Family Labor	0.078	0.017	4.64	0
Hired Labor	0.073	0.017	4.22	0
Capital & Materials	0.229	0.012	18.61	0
Rondônia	-0.038	0.059	-0.65	0.52
Acre	0.017	0.071	0.24	0.81
Amazonas	0.178	0.049	3.65	0
Roraima	-0.163	0.073	-2.23	0.03
Para	0.044	0.032	1.36	0.17
Amapa	0.124	0.079	1.55	0.12
Tocantins	-0.023	0.051	-0.46	0.65
Maranhão	0.086	0.034	2.53	0.01
Piauí	0.039	0.038	1.02	0.31
Ceará	0.099	0.023	4.22	0
Rio Grande do Norte	0.052	0.031	1.67	0.10
Paraiba	0.083	0.028	2.95	0
Pernambuco	0.025	0.036	0.7	0.49
Alagoas	0.004	0.040	0.11	0.91
Sergípe	-0.056	0.040	-1.4	0.16
Bahia	-0.012	0.027	-0.44	0.66
Minas Gerais	0.022	0.019	1.2	0.23
Espírito Santo	-0.058	0.038	-1.53	0.13
Rio de Janeiro	0.098	0.032	3.03	0
São Paulo	0.071	0.021	3.4	0
Parana	0.051	0.024	2.07	0.04
Santa Catarina	-0.020	0.032	-0.62	0.53
Rio Grande do Sul	-0.010	0.028	-0.35	0.73
Mato Grosso do Sul	0.070	0.043	1.61	0.11
Mato Grosso	0.025	0.035	0.72	0.47
Goiás	0.053	0.035	1.52	0.13
Federal District	0.058	0.156	0.37	0.71
/mu	-0.321	0.577	-0.56	0.58
/eta	-0.095	0.004	-24.36	0

--continued

Appendix D

Technology Parameter Estimates—continued

Dependent Variable: Land	Coefficients	Standard Error	Z	P>|Z|
/lnsigma2	-0.461	0.409	-1.13	0.26
/ilgtgamma	3.091	0.415	7.45	0
sigma2	0.630	0.258		
gamma	0.956	0.017		
sigma_u2	0.603	0.258		
sigma_v2	0.027	0.001		

Note: The model's log likelihood: 108.37; number of observations = 1,617. All production output and input variables except Time trend are logged.