Brazil's Agricultural Total Factor Productivity Growth by Farm Size[†]

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Abstract

The role of farm size has recently come to the forefront of agricultural development debates. Agricultural development policy often focuses on small farms given evidence of their role in poverty reduction and of higher yields. Yet policy has also focused on large farms due to their share of output, efficiency gains from vertical and horizontal integration, and potential employment generation. Brazil offers an interesting case study because of its wide spectrum of farm sizes and the country's dual agricultural policy focus towards large commercial "agribusiness" enterprises, led by the Ministry of Agriculture, and "family farms," led by the Ministry of Agrarian Development. Our purpose is to examine the role that farm size may have in Brazil's agricultural total factor productivity (TFP) growth, which has accelerated at one of the world's fastest rates over the last twenty years. The data are drawn from the agricultural censuses of 1985, 1995/96, and 2006, aggregated at the municipality level into five farm-size classes. The findings of this study point to heavy technical efficiency losses across all size classes, creating a substantial drag on national agricultural TFP growth. Moreover, because farms in the middle of the size distribution achieved the slowest technical change and TFP growth – bookended by faster growth in the smallest and largest farm-size classes – we identify an unexpected and unexplored source of inefficiency, namely medium-sized farms.

Keywords: productivity, agriculture, Brazil, technical change, efficiency change, farm size, total factor productivity (TFP)

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1. Introduction

Over the past twenty years, Brazil has achieved one of the world's fastest agricultural total factor productivity (TFP) growth rates (Fuglie and Wang, 2012). Recent evidence also suggests that the productive efficiency of Brazil's farmers continues to improve. Gasques (2014) and ERS (2014) show Brazil's 2002-2011 average annual agricultural TFP growth rate has accelerated beyond the previous decade's rate. Evaluations of Brazil's long-term agricultural TFP growth have often centered on: (i) public investments in such areas as agricultural research (Rada and Valdes, 2013; Avila and Evenson, 1995) and transportation infrastructure (Mendes, et al., 2009); (ii) differential productivity growth rates in the crop and livestock sectors (Rada and Buccola, 2012; Ludena, 2010; Avila and Evenson, 1995); (iii) and the role of cropland expansion to the Cerrado (Avila et al., 2013; Gasques et al., 2013; Rada 2013)

Our purpose is to examine the role of farm size in Brazil's recent agricultural success. In particular, we evaluate whether small or large farms have achieved the most accelerated total factor productivity growth and assess resultant policy implications. Utilizing 1985, 1995/96, and 2006 farm-level agricultural census data, aggregated into five farm-size classes and approximately 3,900 Minimum Comparable Areas (AMCs), we estimate a stochastic production frontier to decompose Brazil's agricultural TFP growth into technical change and technical efficiency change.

Results indicate rapid sectoral technical change has occurred since 1985, but that average annual agricultural TFP growth has been slower at 1.74%. The farm-size class achieving the most rapid TFP growth was the smallest (0-5 hectares), followed by the largest (500- hectares). Middling farm-size classes achieved slower TFP growth, such that productivity's distribution over farm sizes is characterized by a U-shape. Two complementary hypotheses may explain Brazil's TFP-size productivity distribution. The first is that large and small farms, each through a separate and unique path, have advantageously adapted or developed size-dependent technologies or processes that has accelerated growth. The second is that Brazilian agricultural policy, through the Ministry of Agriculture and the Ministry of Agrarian Development, has respectively focused on the large and small producers and has, to a certain extent, ignored the needs of middling farm sizes.[1]

Section 2 of this study describes the model and econometric specification to be used. Section 3 discusses the data and variable construction, Section 4 presents descriptive statistics, and Section 5 describes the results. Section 6 concludes the study.

2. Characterizing Brazil's Agricultural Technology

We let $y_{jit} \in \Re_{+}^{M}$, $j = 1...M$ be scalar outputs; $x_{kit} \in \Re_{+}^{N}$, $k = 1...N$ be conventional scalar inputs; $t = 1\ldots S$ be an index of time which reflects technical change; and $i = 1...I$ be the set of observations on technology $T = \{(x_{kit}, y_{jit}, t): x_{kit} \text{ can produce } y_{jit}\} \in \Re_{+}^{\text{N+M}}$. We characterize Brazil's agricultural technology by way of its producible output set, $P(x_{kit}^{o}) = \{y_{jit} \in \Re_{+}^{M} : (x_{kit}^{o}, y_{jit}, t) \in T\}$; that is, the output (y_{jit}) is feasible given fixed inputs (x_{kit}^{o}) and technology *T*.

The deterministic output distance function

(1) $$D_O(x_{kit}, y_{jit}, t) = \inf_{\theta}\{\theta > 0 : \, y_{jit}/\theta \in P(x_{kit}^{o}, t)\} \;\forall\; x_{kit} \in \Re_{+}^{N}$$

[1] We note that the Ministry of Agriculture's complete name is the Ministry of Agriculture, Livestock, and Supply (MAPA).

is dual to the producible output set, and thus accurately depicts technology T. Specifically, if outputs are weakly disposable, equation (1) implies $D_O(\cdot) \leq 1$ if and only if $y_{jit} \in P(x^o_{kit}, t)$. Technical efficiency is maximized if outputs y_{jit} are located on the outer boundary of $P(x^\circ_{kit}, t)$; that is, when θ achieves its maximum value of unity then $D_O(x_{kit}, y_{jit}) = 1$.

Stochastic Frontier Setting

Along a ray from the origin, output distance (1) is an observation's deviation from its frontier. However, unlike in (1), stochastic distance frontier estimates of technical efficiency are not bounded by unity. Lifting this constraint is the technical inefficiency error, which when combined with an idiosyncratic error and expressed in exponential form, gives the stochastic frontier (Aigner, et al., 1977; Meeusen and van den Broeck, 1977):

(2) $$D_O(x_{kit}, y_{jit}, t, \beta) = e^{v_{it} - u_{it}},$$

in which β is a vector of parameters to be estimated; μ_{it} is a strictly positive error representing an observation's distance from the technological frontier; and v_{it} an iid random noise with mean zero and variance σ_v^2 (Aigner, et al., 1977). Inefficiency error μ_{it} is often modeled with the half-normal distribution $u_{it} \sim N^+(\mu, \sigma^2)$, although other distributions are possible. Error terms v_{it} and u_{it} are assumed distributed independently of one another with a zero covariance, $\sigma_{vu} = 0$. Specifying the left-hand side of (2) in exponential form and substituting it into (1) expresses technical efficiency (TE) as

(3) $$TE_{it} = e^{g(\ln x_{kit}, \ln y_{jit}, t; \beta)} = e^{v_{it} - u_{it}}$$

where g is a function.

We model inefficiency error u after Battese and Coelli (1992):

(4) $$u_i = u_i \exp[-\eta(t - S_i)]$$

in which η is a parameter and S_i is the base inefficiency level. In the final time period, $t = S_i$ and hence represents the reference point from which inefficiency in other periods is measured. Substituting (4) into (3) provides

(5) $$e^{g(\ln x_{kit},\ \ln y_{jit},\ t;\ \beta)} = e^{v_{it} - u_i \exp[-\eta(t - S_i)]}.$$

For $e^{g(\ln x_{kit},\ \ln y_{jit},\ t;\ \beta)}$ to be a distance function, we impose the required property of linear homogeneity of degree +1 in outputs. Output linear homogeneity of degree +1 means scaling the output vector in a given positive proportion scales output distance, or technical efficiency, in the same proportion. By imposing output linear homogeneity through normalization, we obtain the dependent variable naturally lacking in distance functions. Output linear homogeneity of degree +1 is maintained by requiring that $D_O(x_{kit},\ \omega y_{jit},\ t;\ \beta) = \omega D_O(x_{kit},\ y_{jit},\ t;\ \beta)$, for any ω>0 (Shephard, 1970). Let $y^*_{jit} = {y_{jit}}/{y_{mit}} \neq +\infty$, $y_{ji} \neq 0$, and $j = 1 \ldots m-1$, in which the m^{th} output is chosen as numeraire (Lovell, et al., 1994). Substituting $\frac{1}{y_m}$ for ω, we then have from (5)

(6) $$e^{g(\ln x_{kit},\ln y^*_{jit},\ t;\ \beta)} = \frac{1}{y_{mit}} e^{g(\ln x_{kit},\ \ln y_{jit},\ t;\ \beta)},$$

and by substituting (6) into (5), taking logs, and rearranging terms brings

(7) $$-\ln y_{mit} = g(\ln x_{kit},\ \ln y^*_{jit},\ t;\ \beta) + u_i \exp[-\eta(t - S_i)] - v_{it}.$$

A more restrictive approach to stochastic frontier estimation may be applied in the presence of a single output. We know from (1) that the output distance function equals the ratio of actual production to maximum potential production, or in the case of a production function,

$E\left(y_{it} \big/ f(x_{kit},\ t,\ \beta) \right)$. Replacing the distance function in equation (2) with a production function yields

$$(8) \qquad y_{it} \big/ f(x_{kit},\ t,\ \beta) = e^{v_{it} - u_{it}}.$$

Note that all previous variable and subscript definitions from equation (2) hold. Re-arranging terms in (8), applying the inefficiency error specified in equation (4), and taking logs generates the production frontier counterpart to the distance frontier specified in equation (7).

$$(9) \qquad \ln y_{it} = f(\ln x_{kit},\ t,\ \beta) + v_{it} - u_i \exp[-\eta(t - S_i)].$$

Technical change (TC) may be estimated from (9) as $TC = \partial f(x_{kit},\ t,\ \beta)/\partial t$, technical efficiency as $E(TE_{it}) = E\left[e^{-u_i \exp[-\eta(t-S_i)]}\right]$, and TFP growth is the sum of technical change and mean technical efficiency change.

Econometric Specification

We measure Brazil's agricultural total factor productivity growth by the more restrictive production frontier approach. The Brazilian agricultural production function $f(\ln x_{kit},\ t,\ \beta)$ is specified with a modified translog functional form:

$$(10) \qquad f(\ln x_{kit},\ t,\ \beta) = \beta_0 + \sum_{k=1}^{N} \beta_k \ln x_{kit} + \frac{1}{2} \sum_{k=1}^{N} \sum_{h=1}^{N} \beta_{kh} \ln x_{kit} \ln x_{hit} + \beta_5 t.$$

Subscript $k = 1,2,3,4$ refers to family labor, capital, purchased inputs, and land. Subscript i indexes the approximately 3,900 AMCs, and t is the time trend indicating census years 1985, 1995-96, and 2006. Time in equation (10) is not specified as a quadratic, or crossed with inputs, because of the limited time-series dimension available from these census data. Substituting the translog specification in to equation (9) yields our econometric model:

(11) $$\ln y_{it} = \beta_0 + \sum_{k=1}^{N} \beta_k \ln x_{kit} + \frac{1}{2}\sum_{k=1}^{N}\sum_{h=1}^{N} \beta_{kh} \ln x_{kit} \ln x_{hit} + \beta_5 t + v_{it} - u_i \exp[-\eta(t - S_i)].$$

3. Data and Variable Construction

It is important to emphasize that the models discussed above will not be estimated with farm level data. All of the data used in this study will be aggregated in order to avoid problems of confidentiality.[2] In order to address the key issues of this research, we aggregate farms by Minimum Comparable Areas (AMCs) and farm size (5 classes).[3,4] The number of municipalities grew from 4,107 in 1985 to 5,548 in 2006. From these municipalities we created 3,861 AMCs. When multiplied by the five farm-size classes that were created within each AMC, the maximum number of observations we could possibly have in each census year—if no data were missing—is 19,305.

Data aggregation implies that we assume homogeneity within each aggregate observation (for example farms with 5 to 10 hectares in the municipality of Viçosa). We call these "representative farms" (RFs), as they reflect the behavior of a group of farms of a given size in a given AMC. The econometric analysis thus explores variation between RFs and across them over time, but due to aggregation, we cannot examine variation within them. This is one reason for emphasizing technological heterogeneity rather than idiosyncratic inefficiency at the farm level. The averaging of the data that result from aggregation should reduce the importance of farm level idiosyncratic inefficiency.

[2] Farm level data can only be accessed in in a secure site at the IBGE headquarters in Rio de Janeiro.
[3] Minimal comparable areas (AMCs) are spatial units that are defined consistently over time. The number of AMCs is smaller than the baseline number of municipalities because sometimes a new municipality is created by taking pieces from several previously existing municipalities. In cases like these, when AMCs are created the municipalities of origin must be aggregated.
[4] The five farm size classes are 0-5 hectares (ha), 5-20 ha, 20-100 ha, 100-500 ha, and greater than 500 ha.

Output growth index

Data problems encountered in the 2006 census data have led us to employ here a deflated aggregate value of agricultural output index rather than a quantity index typical of total factor productivity estimation. It is common in Brazil to deflate using the general price index (IGP-DI). We chose not to do this, as we want our deflator to approximate what would have been obtained had we constructed a quantity index of all agricultural outputs in Brazil. The objective, therefore, is to remove the effect of agricultural prices from the evolution of agricultural value of output, in order to have an approximation of an agricultural quantity index. Because agricultural prices fell substantially in real terms in this period, a general price index like the IGP-DI would not be an appropriate deflator. The value of output was deflated with an implicit price deflator calculated from the data presented in Gasques et al. (2010).[5] Extensions to the present analysis will include Fisher quantity indexes.

Input growth indexes

Quantity indexes are constructed for four types of inputs: land, family labor, the stock of capital, and purchased inputs (including hired labor).[6] Because we use a translog functional form that includes linear, quadratic, and interaction terms for all inputs, it is important to be parsimonious in the specification of the inputs in order to limit the number of coefficients that need to be estimated. The quantity indexes are described below.

[5] Gasques et al. (2010) calculate a Tornqvist quantity index from Brazil's agricultural censuses since 1970 and based on 367 products. Using this quantity index and the total value of output in each census year, we were able to calculate the implicit price deflator for 1985, 1996, and 2006 that is appropriate for use with these data.

[6] In the section on robustness we explore whether the main results for TFP growth, technical change and efficiency change are sensitive to further disaggregation of the purchased inputs.

Land

Ideally, we would like to construct a quality-adjusted quantity index of land that distinguishes between different land types, including natural pastures, planted pastures, annual crop land, tree crop land, irrigated land, etc. The census does record land area, specified in hectares (ha), according to these different uses. The problem is a lack of price data in the census that could be used for aggregation. We therefore employ state-level land rental prices from the Getulio Vargas Foundation (FGV) and specific to crops and pastures. Hectares of each land type are aggregated using the ratio of crop to pasture rental rates.[7]

Family labor

How to aggregate labor is always a challenge with Brazil's agricultural census data. The issues include: 1) aggregation of hired permanent and temporary labor, 2) accounting for labor used when subcontractors are hired to do specific tasks (preparation of fields, planting, harvesting, etc.), and 3) aggregation of family labor across men and women, adults and children, and part-time vs. full-time family workers. The 2006 census introduced a number of improvements—including information on days worked by family members, and gender, age, and education of the producer. Unfortunately, because this information does not exist in the prior censuses, it cannot be used consistently over time. We employ a relatively simple, yet consistent, form of aggregating family laborers and expressing them in "male adult equivalents." Expenditures on hired labor and sub-contractors are allocated to the variable capturing all other "purchased inputs." This has the advantage of avoiding assumptions when aggregating labor types.

[7] A possible extension is to try to estimate weights that distinguish rain-fed crop land and irrigated crop land from permanent pastures, following Fuglie (2010). While this would be a desirable improvement, only 1.3% of the land recorded in the 2006 census was irrigated, which represented about 8% of crop land. This is unlikely to make a difference at the aggregate level, although it could be important in certain locations.

In previous work using the 1995-96 agricultural census data (Moreira et al. 2007, and Helfand et al., 2011), state-level information was gathered from the National Household Survey (PNAD) on the average number of hours worked by male and female family members in agricultural activities. Women, on average worked around three quarters of the hours of men. Based on this information, we estimate a measure of family labor in “male adult equivalents”. Estimation weights are 1.00 for men, 0.75 for women, and 0.50 for children under the age of 14. The importance of the weights is diminished somewhat because most family labor is comprised of adult men. In 2006, 92% of family members occupied on the farm were 14 years or older, and 65% of the total were men.

Capital stock

We follow Moreira et al. (2007) and create a quantity index of the stock of capital captured in machines, animals, and tree crops. The machinery capital stock was calculated using the number of tractors (available in five horsepower classes), trucks, pick-up trucks, planters, and harvesters, and respective sale prices from the Instituto de Economia Agrícola in the state of São Paulo. The prices refer only to the state of São Paulo in 1996, but they are the most comprehensive that exist.

The capital stock of animals was calculated as a flow of annual services, specified in “cattle equivalents.” Nine different animal stocks were first converted to annual service flows using 1985 ratios of output value to animal stocks (counts) for the three most important animals—cattle (large), pigs (medium), and chickens (small).[8] The conversion ratios were 0.27 for large animals, 0.63 for medium animals, and 4.12 for small animals. Relative prices from 1985 were then used to aggregate the nine service flows into a single, cattle-equivalent annual

[8] The nine different animals were designated one of the three conversion ratios, depending on animal size.

service flow. Note that we chose not to use time varying conversion ratios because they may reflect the technical change that will be econometrically estimated.

The stock of capital in tree crops was calculated as the present discounted value of the future stream of profits from thirteen different tree crops, following the methodology in Butzer, et al. (2010). Utilizing data on the quantity of trees for thirteen perennial crops, expected years of production, and average regional productivities and prices, we calculated the present discounted value of the future stream of revenues expected from the stock of tree crops.

The three capital stock variables were aggregated to reduce the number of estimated coefficients. Aggregation weights were calculated from regional regressions of the 1985 value of output on the 1985 values of each variable at the municipal/farm size level. The regression results and weights used are shown in Appendix Tables A3 and A4.[9] Machines were the most important component of capital in all regions but the North, where animals dominated. The weight on machines varied between 0.50 and 0.59 in the Southeast, South and Center-West, and dropped to 0.39 and 0.15 in the Northeast and North.

<u>Purchased inputs</u>

The final variable measures expenditures on all other purchased inputs. These variable inputs include spending on hired-labor wages and salaries (18%), fertilizers (16%), pesticides (12%), animals (8%), feed (7%), fuel (6%), electricity (6%), soil correction (4%), medicine (3%), seeds (2%), transportation (2%) and other items. The census data only provide the value of expenditures on each item. Because there is no information on prices or quantities, this category is deflated over time.

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[9] Prior to estimation, we standardized each variable by subtracting its mean and dividing by its standard deviation. The regressions fit the data extremely well, with adjusted coefficients of determination (Adj. R^2) between 0.55 and 0.85. The weights were normalized to sum to one.

Missing values

Missing values were imputed for each variable so as to not lose observations for the econometric analysis. On average the missing values represented about 8% of the observations and 5% of the value of each variable.[10] A relatively precise imputation procedure was developed that relied on known municipal totals. Thus, we first calculated the value of each variable that was missing in each municipality, and then allocated this value across the missing observations in the same municipality based on the average shares for each variable by state and farm size. Thus, by way of example, in a municipality where only R$50 of output was missing, only this amount was imputed to the missing observations in that municipality. In municipalities where R$5,000 was missing, this was the amount distributed across the observations with missing values, where the distribution reflects the average production shares of farms in each size class in each state. As a result of this procedure, the value of a variable with imputation exactly matched the true value at the level of Brazil (absent rounding error in each municipality, and locations that were removed from the data set because the municipal totals were missing).

4. Descriptive Statistics

Descriptive statistics on the main variables to be used in the econometric study are provided below. These include agricultural output, land, family labor, purchased inputs, and the stock of capital embodied in machines, animals and tree crops. The results are reported by region, farm size, and period.

[10] For example, in the cases of output, land, and purchased inputs, between 8% and 8.6% of the 2006 observations were imputed, and the value imputed was between 3% of the total for land and 7.2% of the total for purchased inputs.

Number of farms, area, and output

Table 1 shows that there were 5,175 million farms in Brazil in 2006, using over 330 million hectares of land and producing R$164 billion reais of output.[11] The final three columns of the table reveal that approximately 90% of farms had less than 100 hectares of land. The 2% of farms that had over 500 hectares in Brazil accounted for 56% of total area and 36% of the value of output. There were 255,000 farms (5%) that were classified as "producers without area." They produced less than 1% of the value of output. Because this category did not exist in previous censuses, it is excluded from the econometric analysis in order to ensure consistency over time. It is also excluded from Table 1, and for this reason the farm size shares do not exactly match the Brazil and regional totals.

A regional focus reveals that nearly half of all farms were located in the Northeast, Brazil's poorest region. Yet as columns 5 and 6 show, this region had 23% of the land in agricultural establishments but only generated 18% of the country's output. The Southeast and South were the two regions with the highest value of output per hectare; the shares of national output in both regions roughly double their shares of land (32% vs. 16% in the Southeast, and 27% vs. 13% in the South, respectively). The Center-West and North have been the agricultural frontiers in recent decades, as agriculture has expanded into the Cerrado and Amazon rain forest. Both regions have a relatively small share of producers, but a disproportionately large share of area. With only 6% of the farms in the country, the Center-West has 32% of the land and was responsible for 18% of the country's output.

[11] At an average annual exchange rate of R$2.18 per US$1, this translates into approximately US$ 75 billion.

Table 1
Number of Farms, Area, and Value of output by Region and Farm Size: 2006 [1]

Region/Size (ha)	Farms	Area	Output	Farms	Area	Output	Farms	Area	Output
		Hectares	(1000s of R$)	Share of Brazil			Share of Region		
Brazil	5,175,636	333,680,037	163,986,295				1.00	1.00	1.00
0-5	1,840,807	3,313,885	11,434,903				0.36	0.01	0.07
5-20	1,373,142	14,774,650	23,470,720				0.27	0.04	0.14
20-100	1,234,802	52,604,220	36,170,441				0.24	0.16	0.22
100-500	370,130	75,603,795	32,286,484				0.07	0.23	0.20
500-	101,736	187,383,487	59,584,360				0.02	0.56	0.36
North	475,778	55,535,764	9,141,737	0.09	0.17	0.06	1.00	1.00	1.00
0-5	95,781	146,919	672,193	0.05	0.04	0.06	0.20	0.00	0.07
5-20	75,941	838,524	973,672	0.06	0.06	0.04	0.16	0.02	0.11
20-100	183,915	8,715,008	2,651,309	0.15	0.17	0.07	0.39	0.16	0.29
100-500	72,046	13,196,603	1,890,526	0.19	0.17	0.06	0.15	0.24	0.21
500-	16,939	32,638,711	2,747,713	0.17	0.17	0.05	0.04	0.59	0.30
Northeast	2,454,060	76,074,411	29,218,651	0.47	0.23	0.18	1.00	1.00	1.00
0-5	1,227,356	1,949,868	4,995,547	0.67	0.59	0.44	0.50	0.03	0.17
5-20	517,828	5,175,106	5,354,512	0.38	0.35	0.23	0.21	0.07	0.18
20-100	404,076	16,763,251	5,965,785	0.33	0.32	0.16	0.16	0.22	0.20
100-500	103,149	20,404,139	4,477,704	0.28	0.27	0.14	0.04	0.27	0.15
500-	20,547	31,782,048	7,973,790	0.20	0.17	0.13	0.01	0.42	0.27
Southeast	922,097	54,937,773	52,879,410	0.18	0.16	0.32	1.00	1.00	1.00
0-5	259,074	584,966	2,573,187	0.14	0.18	0.23	0.28	0.01	0.05
5-20	289,721	3,215,442	5,974,011	0.21	0.22	0.25	0.31	0.06	0.11
20-100	256,102	11,219,565	11,875,124	0.21	0.21	0.33	0.28	0.20	0.22
100-500	81,925	16,917,112	13,873,026	0.22	0.22	0.43	0.09	0.31	0.26
500-	15,758	23,000,688	18,418,239	0.15	0.12	0.31	0.02	0.42	0.35
South	1,006,203	41,781,003	43,926,142	0.19	0.13	0.27	1.00	1.00	1.00
0-5	228,480	554,808	2,942,076	0.12	0.17	0.26	0.23	0.01	0.07
5-20	428,900	4,800,918	10,472,925	0.31	0.32	0.45	0.43	0.11	0.24
20-100	264,578	10,140,535	13,236,171	0.21	0.19	0.37	0.26	0.24	0.30
100-500	52,257	11,363,159	7,970,334	0.14	0.15	0.25	0.05	0.27	0.18
500-	12,177	14,921,583	9,112,224	0.12	0.08	0.15	0.01	0.36	0.21
Center-West	317,498	105,351,087	28,820,355	0.06	0.32	0.18	1.00	1.00	1.00
0-5	30,116	77,326	251,900	0.02	0.02	0.02	0.09	0.00	0.01
5-20	60,752	744,660	695,599	0.04	0.05	0.03	0.19	0.01	0.02
20-100	126,131	5,765,862	2,442,050	0.10	0.11	0.07	0.40	0.05	0.08
100-500	60,753	13,722,783	4,074,895	0.16	0.18	0.13	0.19	0.13	0.14
500-	36,315	85,040,456	21,332,394	0.36	0.45	0.36	0.11	0.81	0.74

Notes:
1. The table excludes the category "producer without area."

There is also considerable heterogeneity in the farm size distributions within regions. The Northeast has the largest share of small farms. Half of this region's farms had only 0-5ha, and 67% of farms of this size in Brazil were located in the Northeast. Only 1% of farms in the Northeast had over 500ha. The South is a region that has historically been characterized by a strong tradition of family farms, but in contrast to the Northeast, the modal farm size class in the South is 5-20ha. The Center-West is home to many extremely large farms; 11% of farms in the region had over 500ha, and 2.4% had over 2,500ha (not shown in the table). Farms over 500ha in the Center-West operated 81% of the region's land and accounted for 74% of its output.

Analysis by region and farms size: Output and inputs

Table 2 shows the growth in output and inputs for Brazil and the five macro-regions over the 1985-2006 period. The deflated value of total agricultural production in Brazil grew by 84% over the two decades.[12] Across regions, the Center-West stands out as having the fastest growth over the entire period (234%). Output growth in this region reflects the expansion and subsequent consolidation of the agricultural frontier. Output grew the slowest in the Southeast (55%) and South (65%), the two regions that historically were the most important for agricultural production. Output approximately doubled in the North (Amazon) and Northeast (where a significant share of land is characterized by a semi-arid climate). It is possible that this reflects the beginning of a process of convergence between agriculture in the North and Northeast and the rest of the country.

[12] Much of the output growth (59%) occurred in the second decade. The late 1980s and early 1990s was a very difficult time for Brazilian agriculture as a result of rising inflation, trade liberalization, a withdrawal of credit, and other factors. See Helfand and Rezende (2004) for a discussion of the policy reforms in this period.

Table 2
Variation of Outputs and Inputs for Brazil and Macro-Regions: 1985-06
(percent)[1]

Region	Output[2]	Land[3]	Family Labor[4]	Purchased Inputs[5]			Capital Stock			
				Technology Intermediates	Other Intermediates	Total	Machines[6]	Animals[7]	Trees[8]	Total
Brazil	84	-11	-29	239	123	150	-8	25	19	-1
North	115	-11	-37	410	162	166	52	118	64	72
Northeast	91	-17	-28	303	118	160	21	-13	80	30
Southeast	55	-25	-24	142	107	118	-29	10	8	-19
South	65	-13	-33	175	93	104	-9	4	-15	-8
Center-We	234	6	-10	608	239	332	28	81	-54	37

Notes:
1. Variations calculated as 100 (X_t / X_{t-i} - 1).
2. Value of output in constant 2006 reais.
3. Land in pasture equivalent hectares, calculated from relative land rental rates in each region.
4. Family labor in adult male equivalent units, with male=1, female=0.75, and under 14 years=0.5.
5. Purchased inputs in constant 2006 reais. Technology Intermediates includes purchased seeds, soil correction, fertilizers, pesticides, medicines and animal feeding; and Other Intermediates refers to electricity, machinery rental, contract labor services, hired labor, land rental, storage, agroindustry materials, transportation, sacks and packaging, interest payments and bank fees, taxes, animal purchases, and other.
6. Machine capital measured as the value of the stock of tractors and four other types of machines in constant
7. Animal capital measured as the value of the stock of nine different types of animals in constant 2006 reais.
8. Tree capital measued as the present discounted value of future profits from 13 perennial crops in constant

Output growth can be due to growth in inputs, technological change, and improvements in efficiency. The remainder of Table 2 sheds light on how input growth has varied by region. It is immediately obvious from Table 2 that growth in land (pasture-equivalent hectares) and family labor (male-adult-equivalent laborers) do not explain the growth in output between 1985 and 2006. Farm land actually declined by 11% over the two decades, and the use of family labor fell by 29%. At the level of Brazil, the growth of purchased inputs appears to have been an extremely important factor that contributed to output growth.

Total purchased inputs rose by 150% between 1985 and 2006. Growth in purchased inputs has been tilted more towards 'technology intermediates' than towards 'other intermediates.' The technology intermediates include fertilizer, limestone (for soil correction), pesticide, seeds, feed, and animal vaccine expenditures. The other intermediates include electricity, machinery rental, contract labor services, hired labor, land rental, storage, agroindustry materials, transportation, sacks and packaging, interest payments and bank fees, taxes, animal purchases, and other. At the national level between 1985 and 2006 the technology intermediates grew by 239%, while the other intermediates grew by only 123% (Table 2). Indeed, the technology intermediates increased at a faster rate than did other intermediates in all regions over the entire sample period. In the North, Northeast and Center-West, the technology intermediates grew about 2.5 times faster than the other inputs. In the South and Southeast, the difference was smaller.

Measures of the capital stock in machines, animals and tree crops from Table 2 reveal that there was little change between 1985 and 2006.[13] Thus, as with land and labor, this variable is unlikely to explain Brazil's rapid output growth. But the relative stability of the capital stock masks important changes across the components of capital, regions and farm sizes. As the most important component of the capital stock index, changes in the stock of machines appear to drive the changes in the aggregate stock of capital. The estimated stock of machines declined by 8%

[13] Interestingly, the aggregate capital stock index rose by 6% between 1985 and 1995/96, and declined by 6% between 1995/96 and 2006.

between 1985 and 2006, likely reflecting over-investment in machines in the 1970s and 1980s when credit was heavily subsidized through negative real interest rates. The capital stock of animals increased the most among capital measures, rising 25% between 1985 and 2006. While the number of chickens entering the capital stock calculation nearly tripled in this period, some of the most important gains in animal production likely came through technical change that increased productivity of poultry by reducing the time to slaughter. The capital stock embodied in tree crops rose by 19% between 1985 and 2006. This mostly reflects the evolution of coffee, which accounted for between two-thirds and three-quarters of the total number of trees entering our tree-stock capital measure.

Many of the changes in input usage across regions are broadly similar to the national trends for 1985-2006, with the exception of the Center-West. Land in production declined in four of the five regions. It declined by as much as 25% in the Southeast of Brazil (where the three most populous states are located--São Paulo, Minas Gerais and Rio de Janeiro), and only rose in the Center-West. Family labor contracted in all five regions, declining by as much as 37% in the North. The growth of purchased inputs follows the same pattern across regions as the growth of output: fastest in the Center-West (332%), roughly matching the national average rate in the North and Northeast, and slowest in the Southeast and South (104%). In all regions, however, spending on purchased inputs rose more quickly than the real value of output. The capital stock grew most quickly in the North (72%), Northeast (30%) and Center-West (37%). The estimated stock of capital actually declined in the Southeast and South, mostly as a result of a fall in the stock of machinery capital.

Table 3 presents the growth of output and inputs by region and farm size. Contrary to what one might have expected, in Brazil there is not a monotonic relationship between farm size and growth in output. Output grew most rapidly (159%) for the largest farms—those over 500 hectares—and for the smallest farms (102%)—those with less than five hectares of land. Growth was slowest (43%) for farms with 100-500 hectares. The pattern of declining land and family labor that was observed across all regions but the Center-West is also present in all farm-size classes with a single exception—family labor for farms with more than 500 hectares. Because large farms are much more likely to hire labor, family labor is only a small share of total labor used for this group.

The growth patterns by farm size across regions are broadly similar, with a few exceptions. Output grew fastest in the largest farm-size class in all regions except the South, where output roughly doubled for both the smallest and largest farms. The fastest growth in output was observed for farms over 500 hectares in the Center-West, rising by more than 300%. In many cases, it appears that farms in the middle of the distribution grew the slowest. This was the case for farms between 20 and 500 hectares in the Northeast, Southeast and South. Land and labor declined in nearly all size classes and regions other than for the smallest farms in the Southeast, and for many size classes in the Center-West. Purchased inputs more than compensated for declining land and labor. They grew faster than output in 19 of 25 cases, and sometimes the difference between the two growth rates was substantial.

Table 3
Variation of Outputs and Inputs by Farm Size and Region: 1985-06
(percent)

Region/Size (ha)	Output	Land	Family Labor	Purchased Inputs: Technology Intermediates	Purchased Inputs: Other Intermediates	Purchased Inputs: Total	Capital Stock: Machines	Capital Stock: Animals	Capital Stock: Trees	Capital Stock: Total
Brazil										
0-5	102	-26	-27	56	137	106	52	25	146	60
5-20	76	-12	-31	94	88	91	7	28	69	18
20-100	53	-10	-28	62	60	61	-22	34	31	-12
100-500	43	-16	-34	156	63	96	-18	15	1	-12
500-	159	-9	4	527	190	285	11	27	-42	11
North										
0-5	100	-46	-28	165	92	89	275	-26	48	13
5-20	78	-31	-52	175	44	51	145	74	39	52
20-100	116	-6	-32	241	147	130	63	152	143	110
100-500	93	-14	-43	255	150	134	48	128	18	65
500-	156	-11	-9	590	206	218	42	115	-22	62
Northeast										
0-5	118	-30	-31	64	156	126	333	-25	291	149
5-20	146	-6	-25	83	88	85	148	4	279	150
20-100	57	-6	-21	35	33	32	21	4	47	28
100-500	19	-20	-30	41	40	43	-25	-14	14	-13
500-	166	-22	-2	899	250	395	0	-26	-30	-10
Southeast										
0-5	78	7	8	25	104	70	13	127	83	34
5-20	64	-8	-24	109	112	110	-2	47	54	13
20-100	32	-24	-36	35	62	51	-37	24	20	-22
100-500	31	-31	-41	100	66	78	-37	-7	3	-26
500-	99	-23	-11	374	167	217	-28	-27	-41	-30
South										
0-5	103	-24	-25	107	198	128	35	50	2	35
5-20	58	-19	-37	106	84	75	-2	17	-25	-1
20-100	53	-18	-38	93	74	66	-21	15	32	-18
100-500	53	-2	-15	328	72	142	-5	0	-41	-6
500-	99	-14	38	258	129	142	6	-31	-73	-1
Center-West										
0-5	86	-39	-39	182	225	190	-13	83	-63	-2
5-20	109	26	-20	239	190	190	28	174	-39	45
20-100	148	43	12	195	132	146	1	142	0	18
100-500	99	1	-25	180	103	122	-6	63	-72	3
500-	317	5	16	855	310	441	54	75	-94	58

Notes: See Table 2.

For farms over 500 hectares in the Northeast, for example, output rose by 166% while purchased inputs rose by nearly 395%.

A surprising result is that the stock of capital grew much more quickly for farms smaller than five hectares (60%) than for any other size class at the level of Brazil. The next largest increase was 18% for farms with 5-20 hectares. Interestingly, the growth in the capital stock of the smallest farms did not take place in the regions where the capital stock grew most quickly (North and Center-West). The capital stock of small farms grew most quickly in the Northeast (149%), the poorest region in the country, and this growth was led by increases in machine capital (333%) and tree crop capital (291%). For several decades, the World Bank and state governments in the Northeast have been developing anti-poverty programs in the Northeast, one component of which was mechanization. It is likely that there is a connection. In contrast to small farms, most of the growth in the capital stock of large farms took place in the Center-West and North. Medium- and large-sized farms in the South and Southeast appear to be lagging.

Purchased inputs appear to be substituting for declining land and family labor. Like output, they rose fastest for farms over 500 hectares (285%) and those under five hectares (106%). The growth of purchased inputs by farm-size differs considerably for technology intermediates relative to total purchased inputs. For total inputs, Table 3 shows that growth across farm size classes exhibits a U-shape at the level of Brazil. The pattern does not hold in all regions, however. Across regions, the most strikingly consistent pattern is the rapid growth of total purchased inputs for farms over 500 ha.

Examining the by-farm size dimension of growth in technology and other intermediate inputs, we find at the national level that the smallest farms (0-5 ha) experienced greater growth in other intermediates, while farm-size classes above 100 ha experienced greater growth in the technology intermediates (Table 3). Farms between 5 ha and 100 ha display similar growth rates for both types of intermediates. The same pattern can be observed in most regions of the country: while farms less than 5 ha generally experienced greater growth in other intermediates, farms between 5 and 100 ha had roughly equal growth between the two sets of intermediate inputs, and farms over 100 ha had much faster growth in the technology intermediates. The North is the one clear exception, with technology intermediates growing faster in all size classes.

There are several hypotheses that could explain the patterns described above. First, the rapid growth of technology-intermediate inputs in the Center-West and North—for nearly all farm sizes—could be related to the generally low natural quality of the soils in those regions. The soils of the Amazon and Cerrado biomes may be characterized as acidic and of low natural fertility. Indeed, Rada (2013) found that 49% of national fertilizer expenditures in 2006, and 48% of pesticide expenditures, source from the Cerrado biome. Second, both of these regions have experienced growth in annual crops on lands that used to be for extensive cattle production, and an intensification of cattle production, that could contribute to explaining the rapid growth of the technology inputs. Third, the growth of technology-intermediate and capital inputs in the Northeast is likely related to increased production of fruits and other perennial crops in places like the São Francisco valley. Finally, growth of technology inputs in the South is probably connected to the rapid growth of chicken and pig production in that region.

Municipal level data on output and inputs for the econometric analysis

Tables 4 and 5 provide information on the distributions of the changes in the variables that were used in the econometric analysis. For each variable, we removed the 0.5% largest and 0.5% smallest observations in order to remove potential outliers. Finally, a few percent of the observations were lost when we calculated variations of the form Q_{06} / Q_{85} because they had zero values in 1985. The final number of observations used to construct the statistics in Table 4 ranges between 18,123 and 18,348, depending on the variable.

Table 4 shows the distribution of the changes in each variable between 1985 and 2006 for Brazil and the five macro-regions. Whereas Table 2 showed that output grew by 84% at the level of Brazil, the median and mean growth rates across the 18,286 RFs were 29% and 137%, respectively. Because the means in Tables 4 and 5 are unweighted, it is more informative to focus on the median. Mean growth can also differ from Table 2 because the data used in Tables 4 and 5 were trimmed to remove outliers. Thus, the median RF grew considerably slower than the national average. Table 4 also reports the variation at the 10th and 90th percentiles of the distribution. They show that the top 10% of RFs experienced output growth of 404% or greater, while the bottom 10% experienced declines in output of at least 68%. Clearly, there is an enormous amount of heterogeneity in the data.

Table 4
Descriptive Statistics of AMC Level Changes for Brazil and Selected Regions: 1985-06
(percent)

	1985-06					
	Obs.	Mean	SD	Percentiles		
				10%	50%	90%
Brazil						
Value of output	18,286	137	363	-68	29	404
Land	18,344	1	89	-64	-20	75
Family labor	18,348	2	109	-70	-28	93
Purchased inputs	18,346	214	484	-61	74	562
Capital stock	18,123	71	293	-81	-11	250
North						
Value of output	982	239	504	-79	59	786
Land	963	25	145	-86	-23	196
Family labor	968	31	161	-83	-29	231
Purchased inputs	906	305	664	-82	85	927
Capital stock	969	130	383	-94	9	441
Northeast						
Value of output	6,318	133	393	-73	15	388
Land	6,341	-5	81	-65	-22	59
Family labor	6,341	0	104	-70	-26	82
Purchased inputs	6,276	189	443	-67	64	497
Capital stock	6,217	91	318	-87	-7	333
Southeast						
Value of output	6,648	121	334	-69	20	373
Land	6,692	-1	86	-64	-23	76
Family labor	6,692	-2	109	-72	-32	93
Purchased inputs	6,690	208	500	-69	60	576
Capital stock	6,600	53	278	-81	-23	204
South						
Value of output	2,987	129	304	-53	48	349
Land	3,005	0	76	-55	-16	60
Family labor	2,995	-6	83	-64	-28	65
Purchased inputs	2,947	197	420	-48	85	485
Capital stock	2,992	42	204	-66	-5	156
Center-West						
Value of output	1,351	177	342	-45	79	471
Land	1,343	26	110	-49	-4	124
Family labor	1,352	21	129	-61	-18	136
Purchased inputs	1,324	336	580	-18	168	773
Capital stock	1,345	93	326	-68	9	249

Notes: See Table 2.

The change in land and family labor across RFs is very similar to the national average. These variables declined by 11% and 29% at the level of Brazil (Table 2). At the median of these distributions, there were declines of 20% and 28%. The capital stock also declined by 11% at the median of the distribution. The median growth of purchased inputs (74%) is larger than the median growth in output. The top 10% of RFs experienced impressive growth in purchased inputs of at least 562%. Thus, once again, we see that purchased inputs appear to be the most important variable explaining the growth in output at the level of Brazil.

In examining the data across regions, we note that the median growth of all variables in the Center West was higher than the national average (or the declines were smaller). The North also experienced faster growth in output, purchased inputs and capital than the country as a whole. These two regions tended to exhibit much higher variability in the data as well. In the North for example, growth of output at the 10th and 90th percentiles was lower and higher, respectively, than in any other region.

Table 5 shows the distributions of the variables by farm size rather than by region. When examining the medians of the changes in output, the picture is somewhat different than what emerged with the aggregate data in Table 3. The farms over 500 hectares no longer dominate the growth of output. Here, the 0-5 hectare group experiences the fastest growth, and the three smallest size classes all grow faster (at the median) than the farms over 500 hectares. In fact, at the 10th, 50th and 90th percentiles, farms with less than 5 hectares experienced faster output growth (or smaller contractions) than farms over 500 hectares. Thus, the entire distribution of growth for small farms—or at least those between the 10th and 90th percentiles—appears to dominate the distribution of growth for large farms.

Table 5
Descriptive Statistics of AMC Level Changes by Farm Size: 1985-06
(percent)

	1985-06					
	Obs.	Mean	SD	Percentiles		
				10%	50%	90%
Brazil 0-5 ha						
Value of output	3,710	215	463	-68	59	637
Land	3,711	19	123	-75	-19	156
Family labor	3,721	30	149	-78	-18	189
Purchased inputs	3,716	381	675	-59	150	1,033
Capital stock	3,634	175	442	-86	21	597
Brazil 5-20 ha						
Value of output	3,787	148	350	-59	44	409
Land	3,781	6	87	-58	-15	79
Family labor	3,792	-5	94	-69	-28	70
Purchased inputs	3,800	208	400	-49	103	518
Capital stock	3,765	116	320	-72	22	355
Brazil 20-100 ha						
Value of output	3,808	96	270	-56	27	274
Land	3,810	-10	61	-55	-21	35
Family labor	3,815	-18	74	-64	-33	31
Purchased inputs	3,816	129	273	-51	62	336
Capital stock	3,792	40	200	-70	-11	172
Brazil 100-500 ha						
Value of output	3,757	81	281	-67	6	241
Land	3,776	-8	70	-58	-22	41
Family labor	3,768	-14	71	-66	-30	42
Purchased inputs	3,771	122	326	-59	41	314
Capital stock	3,748	10	161	-76	-23	96
Brazil 500- ha						
Value of output	3,224	149	409	-85	16	485
Land	3,266	0	90	-72	-21	84
Family labor	3,252	19	129	-76	-19	150
Purchased inputs	3,243	236	592	-82	52	650
Capital stock	3,184	9	209	-99	-39	104

Notes: See Table 2.

In order to explain the difference with Table 3, it is important to recall that the data in Table 3 was first aggregated before calculating the changes for each group. Thus, the observations were weighted by their values. Here, the changes are first calculated for each observation, and then we calculate the mean and median of the distribution of changes. It is likely that there is a small number of large farms that both grew very rapidly *and* had a large share of the output of large farms. They would get little weight here, and much more in Table 3. The same logic, in reverse, is true for the small farms.

Finally, median purchased inputs and the capital stock both decline monotonically as farms size grows. The median changes in land and labor, in contrast, are fairly similar for all farm sizes.

There is an enormous amount of heterogeneity to be explored across municipalities and farm sizes. The Center-West and large farms appear to be the most dynamic, but there is also evidence that many small farms might be increasing output and inputs at comparable rates. Farms in the Southeast and South, and in the middle of the size distribution, might be the ones that—on average—are achieving lower efficiency levels.

5. Results

The econometric model specified in equation (11) was estimated by STATA/MP 13.1, using the *xtfrontier* command. Regressions employed representative farms (RFs) and state-fixed effects, and were individually estimated at different levels of aggregation: national, regional, and by farm size.[14] The models were estimated with observations weighted by output shares, rescaled to leave

[14] Prior to estimation the panel was balanced and approximately 7.5% of the representative farms (RFs) were lost. This resulted from RFs that did not have data in all three years, had confidentiality imposed in one or more years, and due to the filtering of outliers. In some cases, during estimation, a regional model would not converge to a solution. In these cases, outliers were re-examined until convergence of the maximum likelihood function was achieved. These are noted with footnotes to the relevant tables.

the number of observations unchanged. Technical efficiency averages were weighted in the same way. Specification tests are provided in Tables 6-9. Coefficient estimates of the production frontier are provided, for the national-level aggregate and by-farm size regressions, in Appendix Tables A5-A10. Tables presenting national, regional, and national by-farm size TFP growth decomposition estimates of technical change and technical efficiency change are provided in Tables 10 and 11. Similar regional estimates by-farm size are provided in Tables 12-16.

Specification Tests

Following Battese and Coelli (1992), log-likelihood ratios were used to test model specifications and hypotheses regarding parameters of the stochastic production frontier. Three sets of tests were conducted. The first set of tests relates to the specification of the model used to estimate TFP at the level of Brazil (Table 6). Second, we examine monotonicity of the partial elasticities for the Brazil model (Table 7). The elasticities are evaluated at the sample mean of the data. Finally, we test the appropriateness of a pooled national model vs. regional models (Table 8) and by farm-size models (Table 9). After rejecting the pooled national model, Tables 8 and 9 reproduce the tests in Table 6 regarding the specification of each individual regional and farm-size model.

The first specification test compares the Cobb-Douglas (CD) functional form to the translog (TL). The null hypothesis is that all of the interaction and second order terms equal zero. The null is rejected at a high level of statistical significance (χ^2=779.85). In fact, all tests in Table 6 reject the null at a level of statistical significance of at least 1%. The second test compares a translog with a single intercept vs. a translog with state-fixed effects. The single-intercept model is rejected in favor of the model with fixed effects (χ^2=889.34).

The next set of tests use a translog production function with state-fixed effects. In these tests, an average (OLS) production function is rejected in favor of a frontier specification, a time-invariant inefficiency error model is rejected in favor of a time-varying error model, and a half-normal distribution for the inefficiency effects is rejected in favor of a truncated normal distribution.

Table 6
Specification Tests at Country Level

Null hypothesis H_0	χ^2 statistic	χ^2 0.95 value (*df*)	Decision	Choice
Brazil				
CD vs. TL[1]	779.85	18.31 (10)	Reject H_0	TL
TL w/o FE vs. TL with FE by Stat	889.34	38.89 (26)	Reject H_0	TL with FE by State
Brazil TL with FE by State				
$\gamma = \mu = \eta = 0$	533.37	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	527.54	5.99 (2)	Reject H_0	Time-variant[3]
$\mu = 0$	280.67	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	501.01	3.84 (1)	Reject H_0	Time-variant

Notes:
1. CD is Cobb-Douglas production function, and TL is Translog production function.
2. FE refers to fixed effects.
3. Null hypothesis H_0 assuming half-normal as a distribution for the inefficiency effects.

The input elasticities presented in Table 7 were obtained by partially differentiating equation (11) with respect to each input. The function coefficient (which measures returns to scale) is defined as the sum of the partial elasticities:

$$(12) \qquad e_{kit} = \frac{\partial \ln y_{it}}{\partial \ln x_{kit}} = \beta_k + \beta_{k1} \ln x_{kit} + \beta_{k2} \ln x_{kit} + \beta_{k3} \ln x_{kit} + \beta_{k4} \ln x_{kit} \qquad e_{it} = \sum_{k=1}^{K} e_{kit} \ ,$$

where e_{kit} is the elasticity of input *k* for representative farm *i* at time *t*, and e_{it} is the function coefficient with k=1,…,4 representing area, family labor, purchased inputs, and capital. The elasticities of a translog depend on the input levels, and can be calculated for each observation i. For simplicity, the elasticities are calculated at the sample means.

Table 7
Elasticities for the Translog Production Frontier

Model / Year	Land	Family Labor	Purchased Inputs	Capital	Total (Function Coefficient)
Brazil / 1985-06	0.08	0.21	0.62	0.13	1.03

All partial elasticities in Table 7 are positive, indicating that monotonicity holds at the mean of the data. The relative magnitude of the elasticities reinforces some of the conclusions from the descriptive tables presented above. They show the overwhelming importance of purchased inputs, with an elasticity of 0.62 for the entire period, followed by family labor (0.21) and capital (0.13). The elasticity for land is the smallest among the four inputs, suggesting that land expansion only makes a relatively small contribution to output growth. The final column of Table 7 shows that returns to scale are close to 1 in all years, suggesting that returns to scale are approximately constant at the level of Brazil. For the mean of the entire period the function coefficient equals 1.03.

Regional specification tests are presented in Table 8. As in Table 6, all null hypotheses are rejected at an extremely high level of statistical significance. In the first test, a restricted pooled model with identical coefficients across regions is compared to an alternative model in which all parameters in the translog are interacted with macro region dummies. The pooled model is rejected in favor of individual regional models. The remainder of the tests explores the appropriate specification for the production function in each region. In all cases, an average production function is rejected in favor of a stochastic frontier production function, a time-invariant inefficiency model is rejected in favor of a time-varying model, and a half-normal distribution for the inefficiency effects is rejected in favor of a truncated normal distribution.

The specification tests for individual farm size models are presented in Table 9. The results are very similar to what was presented in Table 8. A pooled model for all of Brazil is rejected in favor of individual models for each farm size class. For each farm size model, the tests indicate that the preferred model should be a stochastic frontier with a truncated normal distribution for the inefficiency term that is permitted to vary over time.

Table 8
Specification Tests of Pooled vs. Regional Models

Null hypothesis H_0	χ^2 statistic	χ^2 0.95 value (*df*)	Decision	Choice
Pooled vs. Regional Models	1,641.35	83.68 (64)	Reject H_0	Regional Models
Regional Models, Translog with Fixed Effects by State				
North				
$\gamma = \mu = \eta = 0$	44.24	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	43.49	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	44.35	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	41.00	3.84 (1)	Reject H_0	Time-variant
Northeast				
$\gamma = \mu = \eta = 0$	140.96	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	140.98	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	33.79	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	140.98	3.84 (1)	Reject H_0	Time-variant
Southeast				
$\gamma = \mu = \eta = 0$	115.49	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	115.10	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	67.02	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	112.00	3.84 (1)	Reject H_0	Time-variant
South				
$\gamma = \mu = \eta = 0$	132.22	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	131.44	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	79.05	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	122.68	3.84 (1)	Reject H_0	Time-variant
Center-West				
$\gamma = \mu = \eta = 0$	142.75	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	109.53	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	89.25	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	46.82	3.84 (1)	Reject H_0	Time-variant

Notes:

1. The null hypothesis H_0 assumes a half-normal distribution for the inefficiency effects.

Table 9
Specification Tests of Pooled vs. Farm-size Models

Null hypothesis H_0	χ^2 statistic	χ^2 0.95 value (*df*)	Decision	Choice
Pooled vs. Farm-size Models	845.27	83.68 (64)	Reject H_0	Farm-size Models
Farm-size Models, Translog with Fixed Effects by State				
0-5 ha				
$\gamma = \mu = \eta = 0$	48.19	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	48.18	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	25.13	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	48.19	3.84 (1)	Reject H_0	Time-variant
5-20 ha				
$\gamma = \mu = \eta = 0$	94.17	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	94.00	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	38.14	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	92.68	3.84 (1)	Reject H_0	Time-variant
20-100 ha				
$\gamma = \mu = \eta = 0$	147.83	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	147.83	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	64.91	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	147.81	3.84 (1)	Reject H_0	Time-variant
100-500 ha				
$\gamma = \mu = \eta = 0$	120.91	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	120.90	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	91.48	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	99.92	3.84 (1)	Reject H_0	Time-variant
500 ha and more				
$\gamma = \mu = \eta = 0$	74.88	7.81 (3)	Reject H_0	Stochastic frontier
$\mu = \eta = 0$	73.03	5.99 (2)	Reject H_0	Time-variant[1]
$\mu = 0$	23.11	3.84 (1)	Reject H_0	Truncated-normal
$\eta = 0$	68.64	3.84 (1)	Reject H_0	Time-variant

Notes:

1. The null hypothesis H_0 assumes a half-normal distribution for the inefficiency effects.

National and regional productivity growth

Total factor productivity was estimated using 16,987 RFs, themselves an aggregation of Brazil's 4.92 million farms.[15] We find Brazil's 1985-2006 average annual agricultural TFP growth to have been 1.74%, composed of 5.0% technical change and -3.26% technical efficiency change (Table 10). Prior to evaluating the by-farm size TFP growth decompositions, we first compare our national and regional estimates with evidence from the literature. Rada and Buccola (2012) employ micro-region-aggregated data in a stochastic input distance frontier specification and estimated Brazil's 1985-2006 average annual technical change to have been 4.54%, very close to our own estimate. Yet Rada and Buccola find technical efficiency losses to be smaller, leading to a higher (2.62%) average annual TFP growth rate than what we find in the present study.[16] We suspect that estimating a multi-output technology, which allows for more similar output comparisons (e.g. crops and animal products), may lead to lower efficiency losses than estimating an aggregate production technology. We also suspect that measured inefficiency is higher with the much more disaggregated data that we have here.

Other studies using Brazil's agricultural census data employ longer time-series, and a Tornqvist-Theil index number approach. Index number approaches to TFP growth estimation do not allow for TFP decomposition into technical change and technical efficiency change; rather, they reflect the performance of an average (efficient) producer. Avila, et al. (2013) find Brazil's 1975-2006 average annual TFP growth to have been 2.16%, and Gasques et al. (2012) find Brazil's 1970-2006 average annual TFP growth to have been 2.27%, and over the 1995/96-2006 period they estimate 2.33%. We hypothesize that the lower level of data disaggregation and

[15] As previously mentioned, producers without area are excluded from the present study. This category accounted for 255,000 producers, and for this reason the total number of farms included does not equal the 5.175 million reported in the official census publication.

[16] In an alternative specification of the Rada and Buccola (2012) model, Rada and Valdes (2012) estimate average annual 1985-2006 technical change to have been 4.4% and TFP change 2.55%.

Table 10
Total Factor Productivity Growth Decomposition in Brazil and by Macro-Region, 1985-2006
(percent per year)

Variable	Brazil	North	Northeast	Southeast	South	Center-West
Total factor productivity decomposition[1]						
Technical change	5.00	7.09	6.29	4.25	4.06	-2.81
Technical efficiency change	-3.26	-4.28	-3.53	-2.73	-2.79	4.48
Total factor productivity change	1.74	2.80	2.76	1.52	1.27	1.67
TFP change at 90th percentile	2.48	4.04	4.41	2.14	1.76	2.07
TFP change at 10th percentile	0.85	1.40	1.05	0.77	0.73	1.21
Complementary data from 2006						
Output (R$1000s) and regional shares[2]	163,986,295	0.06	0.18	0.32	0.27	0.18
Number of farms and regional shares[2]	4,920,617	0.09	0.47	0.18	0.19	0.06
Representative farms	16,987	847	5,831	6,289	2,754	1,254

Notes:

1. All estimates are weighted by output shares.
2. Number of farms excludes "producer without area."
3. Twelve RFs were removed from the Center-West model in order to achieve convergence.

greater capital-input accounting of the present study are likely reasons why the Table 10 TFP growth estimate is slower than that found in previous studies.

Of particular importance to the present study is the regional productivity detailed in Table 10. The Brazilian North and Northeast have achieved rates of technical change and TFP growth that have exceeded the national average, while those in the Southeast, South, and Center-West have rates that have lagged behind the national average. That TFP growth in the North and Northeast has been faster than growth in the more southern regions is not altogether unexpected. The North and Northeast account for respective 6% and 18% shares of output in 2006, and growth from a small base can more easily generate larger changes than growth measured from a large base. Moreover, Rada and Buccola (2012) found 1985-2006 average annual TFP growth in an aggregate of the North and Northeast (1.96%) was larger than in an aggregate of the South, Southeast, and Center-West (1.29%). Faster TFP growth in the North and Northeast does, importantly, suggest that there may likely be a process of convergence of productivity levels occurring across regions in Brazil.

The regional TFP growth rates exhibited in Table 10, however, show strong dissimilarities with regional estimates from Avila, et al. (2013).[17] For instance, over the 1975-2006 censuses, Avila, et al. find TFP growth to have been most rapid in the Center-West (2.8%), with the Southeast (2.67%), Northeast (2.20%), and South (2.14%) all exceeding growth in the North (1.23%). One immediate difference between these estimates and our own is the difference in time period. However, one might not expect such drastic changes in regional growth over the 1975-85 census periods to solely determine the TFP growth differences present with Avila, et al. Reconciling result differences between Avila, et al. and our own study will be a focus of future research.

[17] Gasques et al. (2012) provide state and national TFP growth estimates but not regional estimates.

The Center-West results found in Table 10 are highly unusual; we estimate negative technical change but positive efficiency change leading to positive TFP growth. The way in which technical efficiency is modeled may explain this result. Recall from equation (4) that we define the inefficiency error as $u_i = u_i \exp[-\eta(t - S_i)]$. Here, a single cross-sectional, half-normal inefficiency distribution is being modeled, in which the sign and magnitude of η respectively determine whether inefficiency is rising or falling over time and the rate of growth. The apparent implications on the inefficiency estimates are that no observation can switch efficiency rankings over time. We therefore interpret the Center-West's negative technical change and positive technical efficiency change in Table 10 as reflecting efficiency rankings in which some of the most-efficient observations decelerated growth relative to the average, while some average-efficient observations achieved accelerated growth rates (relative to those on the frontier). The regional by-farm size estimates of the Center-West's TFP decomposition (below) shed additional light on these results.

Beyond the regional heterogeneity presented in Table 10, we are also interested in the distribution of TFP growth over farm-size classes. Because technical change and TFP growth may be interpreted as the productive efficiency change of the most-efficient and average producers, Table 10 presents TFP growth estimates of Brazil's most-efficient RFs (estimated by the rate of technical change), of the RFs in the 90th percentile of efficiency, of average RFs (i.e. average TFP growth typical in the literature), and of the RFs in the 10th percentile of efficiency. From this perspective, we find mean per-annum 1985-2006 TFP growth of Brazil's most-efficient RFs was 5.0%, of the 90th percentile was 2.48%, of the average RF was 1.74%, and of the 10th percentile was 0.85%. These distributional estimates are further provided for each region (Table 10). The most-efficient RFs which accelerated their TFP growth at the fastest rate were operating in the North (i.e., the North has the highest rate of technical change), while those 90th percentile-efficient RFs which accelerated their TFP growth at the fastest rate were in the Northeast. The most rapid average TFP growth rates were very similar in the North and the Northeast. Brazil's least efficient producers are represented by the 10th percentile category, and of those, the South's and Southeast's 10th percentile-efficient RFs were the most sluggish.

National productivity growth by farm size

While the national and regional productivity estimates are of interest to allow for result comparisons, the primary purpose of the present study is to examine Brazil's farm-size performance differences. To this end, Table 11 replicates the national TFP decomposition detailed in Table 10, but expresses variation across farm sizes rather than regions.

Immediately noticeable in Table 11 is that technical change and TFP growth are greatest in the smallest size class (0-5 ha). This is likely a reflection of important changes taking place within this size class for at least a share of these farms. And because 36% of all farms have less than five hectares, the relatively high performance should be welcome news to Brazil's policymakers who keep the role of small farms, with implications for national food security and poverty reduction, at the forefront of agricultural development policy. The second fastest TFP growth rate is achieved by Brazil's largest farm-size class (500- ha). This class accounts for 2% of all farms in Brazil, but accounts for 36% of national output, making the class' 2.3% average annual TFP growth rate all the more impressive.

Somewhat unsurprisingly, we find TFP growth declines with size, at least initially. Technical change declines rapidly from 7.05% per annum for the 0-5ha class to 4.57% per annum for the 5-20 ha class, to 3.76% for the 20-100 ha class, while respective size-class TFP growth falls from 2.62% to 1.63% to 1.14%.

Table 11
Total Factor Productivity Growth Decomposition in Brazil by Farm Size, 1985-2006 (percent per year)

Variable	Brazil	Farm Size Class (hectares)				
		0-5	5-20	20-100	100-500	500-
Total factor productivity decomposition[1]						
Technical change	5.00	7.05	4.57	3.76	5.12	4.94
Technical efficiency change	-3.26	-4.43	-2.93	-2.62	-3.83	-2.64
Total factor productivity change	1.74	2.62	1.63	1.14	1.29	2.30
TFP change at 90th percentile	2.48	3.72	2.56	1.91	1.98	2.89
TFP change at 10th percentile	0.85	1.13	0.59	0.31	0.38	1.66
Complementary data from 2006						
Output (R$1000s) and size shares[2]	163,986,295	0.07	0.14	0.22	0.20	0.36
Number of farms and size shares[2]	5,175,636	0.36	0.27	0.24	0.07	0.02
Representative farms	16,987	3,058	3,719	3,738	3,658	2,814

Notes:

1. All estimates are weighted by output shares.
2. Shares do not sum to one because they exclude "producer without area," a category that did not exist in previous censuses. Producers without area accounted for 4.9% of all farms in 2006, and 0.6% of output.

(Table 11). However, we find technical change and TFP growth re-accelerate for larger farms. These results are similar to those from Helfand and Levine (2004) who find Brazil's 1996 technical efficiency-size relationship in the Center-West had a U-shape, where TFP declined until some inflection point (which they find differs by type of producer) at which point efficiency rose. We too find a U-shape to reflect the relationship between TFP change and size, the inflection point likely captured within the 20-100 ha size class. The 20-100 ha size class accounts for 22% of national output and 24% of all producers but has had the slowest technical change and TFP growth. That this size class contains a substantial proportion of Brazil's output and farms, yet is achieving such slow advances in TFP, should be cause for concern among Brazil's policymakers.

Further findings from Table 11 focus on performance dispersions. The first relates to the 0-5 ha size class, whose most-efficient producers have accelerated their TFP growth at 7.05%, while the 90th percentile of producers in that class have achieved a TFP growth rate of only 3.72%. This very steep growth difference between the two groups of small farmers (3.33%) is of the same magnitude as the difference between the largest-size class' (500- ha) most-efficient RFs and the efficiency of that class' 10th percentile of RFs (3.28%). Stated differently, there is more efficiency loss in the smallest size class between its most-efficient producers and those of the 90th percentile than the largest size class has between its most-efficient and some of its least-efficient producers. One possible explanation may relate to the types of technologies employed. For instance, Table 4 shows that technology intermediate inputs grew slowest for farms under 5 ha. This may reflect some inequity in the distribution of inputs, leading to a very small group of smallholder farmers modernizing at a rate much faster than all others. But more broadly it likely reflects the lack of technology intermediates employed, relative to other farm sizes.

The second dispersion notable from Table 11 relates to the performance of the 100-500 ha size class. RFs in this size class achieve the highest technical change outside of the 0-5 ha class, yet also achieve the sample's lowest TFP growth of 1.29% per annum. The large technical efficiency losses in this size class indicate the potential presence of 'technology switching.' That is, while the most-efficient RFs in this class achieved very rapid productivity growth, the average-efficient RF was accelerating productivity at a much slower rate. This result is consistent with findings from Rada and Buccola (2012) who show agricultural-research benefits (e.g. new technologies and practices) from Embrapa were captured by Brazil's most-efficient producers. Average producers, alternatively, likely faced obstacles to upgrading their technology at the same rate, such as credit constraints, learning by doing, and others.

Regional productivity growth by farm size

This section will decompose TFP growth for each farm size within a given region. The sub-sections will be presented in the order of North, Northeast, Southeast, South, and Center-West.

<u>North region</u>

The Brazilian North accounts for 9% of national farms, 17% of national area in farms, and 6% of national output (Table 1). Some may thus consider it the least agriculturally important region of Brazil. Yet, as noted in Table 10, it achieved Brazil's most rapid productivity growth. Table 12 provides the North's TFP growth decomposition, as well as that decomposition across

Table 12
Total Factor Productivity Growth Decomposition by Farm Size in the North Region of Brazil, 1985-2006
(percent per year)

Variable	North	Farm Size Class (hectares)				
		0-5	5-20	20-100	100-500	500-
Total factor productivity decomposition[1]						
Technical change	7.09	8.17	6.58	4.41	6.59	5.56
Technical efficiency change	-4.28	-4.43	-2.94	-1.14	-3.67	-3.76
Total factor productivity change	2.80	3.74	3.64	3.27	2.92	1.79
TFP change at 90th percentile	4.04	5.04	5.45	3.78	4.02	4.09
TFP change at 10th percentile	1.40	2.19	0.73	2.60	1.76	-0.60
Complementary data from 2006						
Output (R$1000s) and size shares[2]	9,141,737	0.07	0.11	0.29	0.21	0.30
Number of farms and size shares[2]	475,778	0.20	0.16	0.39	0.15	0.04
Representative farms	847	136	186	188	184	153

Notes:
1. All estimates are weighted by output shares.
2. Shares exclude "producer without area," a category that did not exist in previous censuses.

farm-size classes. The North achieved Brazil's highest rate of technical change, and that growth has been led by the region's smallest farm-size class (Table 12). The North's 0-5 ha size class accelerated technical change by 8.17% per annum, on average, over the 1985-2006 censuses. Despite this size class also having the largest efficiency losses, it also had the region's highest TFP growth rate of 3.74%. Thus, not only were the size class' most-efficient producers accelerating at a faster rate than other size classes, so too were the average-efficient producers.

Similar to the TFP-size trend shown in Table 10, technical change in the North declined with size until the 20-100 ha farm-size class, and then re-accelerated. Yet differing from all other regions, the relationship between TFP and size is not a U-shape, but rather a negatively sloped trend; TFP is fastest in the smallest farm-size class and slowest in the largest class (Table 12). Surprisingly, the Brazilian North experienced the greatest growth of capital inputs, led by the animal capital measure (Table 2). Although, the machinery and tree-stock capital measures for this region have also grown at greater rates than most other regions. Machinery capital was the component that grew most for the smaller farms, while animal capital was the component that increased most for larger farms. Indeed, the largest farms (500-ha) aggregate capital stock measure increased at a greater rate than any other region, even more than in the Center-West. And growth in output for that largest farm-size class was far slower than what that size class achieved in the Center-West. Thus, the finding of declining TFP-growth with size likely is a result of the study's greater capital accounting. It might also reflect increasing specialization of large farms in cattle, which is often a less dynamic sector.

One reason for the North's relatively rapid TFP growth (2.80%), apart from the low base from which growth has been determined, may be the exclusion of forest land as part of the land input, but the inclusion of forest products in the output measure.[18] This would bias our TFP growth measure upwards if growth of the omitted forest land was faster than growth of the aggregate land measure we presently employ. Moreover, by including agroindustry products, a growth advantage is given to smaller producers who add value to their primary commodity production, such as revenue from cassava flour or cheese.

Much like the region-specific estimates shown in Table 12's column 1, the smallest size class also had substantial performance differences between the most-efficient producers and those in the 90th percentile. Future investigations into the wide performance dispersion within this region should start with the smallest size class, but should also include the 100-500 ha size class due to its own substantial differences among the more efficient producers. Also notable in Table 12 is that 51% of the output is generated on farms of 100 hectares or more, yet these farms achieved the region's slowest TFP growth. Agricultural extension efforts might be targeted to these larger farm-size classes as a way to mitigate the substantial technical efficiency losses.

<u>Northeast region</u>

Brazil's Northeast region contains 47% of all farms, but only produced 18% of 2006 national production. Unlike the North, the farm-size class that has achieved the highest rate of technical change is not the smallest class, but the second-smallest class (5-20 ha). These farms accounted for 18% of regional production and 21% of regional farms, and have achieved a rapid average annual technical change rate of 7.75% and a brisk TFP growth rate of 4.12% (Table 13). The output weights in Table 13 are rather even across size classes, allowing one size-class to not dominate the regional estimate. For this reason, the 100-500 ha size class may have a slow TFP

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[18] A consequence of using the total deflated value of output, rather than a quantity index, is that all items of production were included.

Table 13
Total Factor Productivity Growth Decomposition by Farm Size in the Northeast Region of Brazil, 1985-2006
(percent per year)

Variable	Northeast	Farm Size Class (hectares)				
		0-5	5-20	20-100	100-500	500-
Total factor productivity decomposition[1]						
Technical change	6.29	5.69	7.75	5.75	5.09	4.88
Technical efficiency change	-3.53	-2.54	-3.63	-3.36	-3.35	-1.96
Total factor productivity change	2.76	3.15	4.12	2.40	1.74	2.91
TFP change at 90th percentile	4.41	4.58	5.82	3.97	3.14	3.99
TFP change at 10th percentile	0.94	1.05	1.95	0.77	0.15	1.19
Complementary data from 2006						
Output (R$1000s) and size shares[2]	29,218,651	0.17	0.18	0.20	0.15	0.27
Number of farms and size shares[2]	2,454,060	0.50	0.21	0.16	0.04	0.01
Representative farms	5,831	1,069	1,287	1,284	1,266	920

Notes:

1. All estimates are weighted by output shares.
2. Shares exclude "producer without area," a category that did not exist in previous censuses.
3. In order to achieve convergence, five RFs were removed from the 20-100 ha model, and two RFs were removed from the 500- ha model.

growth rate of 1.74%, on average each year, but the regional rate has accelerated faster at 2.76%. This differs from the North region, in which the 500-ha size class accounted for 30% of production and therefore its slow TFP growth created a drag on regional TFP growth.

Despite production shares being somewhat evenly distributed across size classes, the number of farms is not. Farms smaller than 20 ha accounted for 71% of the region's farms but produced only 35% of its output (Table 1). Conversely, the two largest size classes accounted for 5% of the region's farms but 42% of its output. It is important to recall, however, that the large farms control 69% of the region's land (Table 1). Table 13 shows that the smallest size classes have accelerated productivity faster than the largest size classes, regardless of whether we examine the most-efficient producers (i.e. technical change) or the average-efficient producers (i.e. TFP growth). Thus, while the smaller size classes in the Northeast may not have produced *as much* as the region's larger size classes, the smaller farms have achieved more rapid productivity gains.

Southeast region

Brazil's Southeast region produces 32% of national 2006 output from 18% of its farms (Table 1). The majority of regional output (61%) sourced from the two largest farm-size classes. However, the three smaller farm-size classes accounted for 87% of the farms. Unlike the Brazilian Northeast where the smallest farms sizes achieved more rapid TFP gains than their larger farm counterparts, in the Southeast the farms over 500-ha have accelerated their TFP growth at the fastest rate (Table 14).

There appears to be no clear technical-change trend over farm sizes in Table 14, although the 100-500 ha size class achieved a national-low 0.73% rate of average annual technical change.

Table 14
Total Factor Productivity Growth Decomposition by Farm Size in the Southeast Region of Brazil, 1985-2006
(percent per year)

Variable	Southeast	Farm Size Class (hectares)				
		0-5	5-20	20-100	100-500	500-
Total factor productivity decomposition[1]						
Technical change	4.25	2.32	4.35	2.61	0.73	3.82
Technical efficiency change	-2.73	-1.22	-3.12	-1.93	-0.59	-1.58
Total factor productivity change	1.52	1.11	1.24	0.68	0.14	2.23
TFP change at 90th percentile	2.14	1.78	2.38	1.27	0.40	2.56
TFP change at 10th percentile	0.77	0.08	0.10	0.11	-0.20	1.85
Complementary data from 2006						
Output (R$1000s) and size shares[2]	52,879,410	0.05	0.11	0.22	0.26	0.35
Number of farms and size shares[2]	922,097	0.28	0.31	0.28	0.09	0.02
Representative farms	6,289	1,150	1,361	1,371	1,293	1,058

Notes:

1. All estimates are weighted by output shares.
2. Shares exclude "producer without area," a category that did not exist in previous censuses.
3. In order to achieve convergence, two RFs were removed from the 0-5 ha model, and 54 RFs were removed from the 100-500 ha model.

Indeed, this size class performs poorly throughout; its average annual TFP growth of 0.14% is the study's slowest. This size class achieved the region's slowest output growth, but also the slowest growth of inputs, except for purchased inputs (Table 3). Given that this size class has produced 26% of regional production, the very slow productive-efficiency improvements warrant further investigation.

Of interest in Table 14 is that TFP growth rises over the first two farm-size classes, and then drops off precipitously, prior to re-accelerating to the fastest regional rate for the largest farms. Performance in the 20-100 ha and 100-500 ha size classes has been very poor and we question what may be acting to dampen efficiency gains. These two size classes did have slower output growth than the largest size class (500-ha), and faster animal- and tree-stock capital accumulation. Potential sources of inefficiency may be size-inappropriate production technologies caused by credit, labor, or knowledge constraints.

<u>South region</u>

As shown in Table 1, the South of Brazil produced 27% of national output on 19% of the farms. The South's smallest size class (0-5 ha) accounted for 7% of regional production but 23% of farms. Conversely, the largest size class (500-ha) has accounted for 21% of regional production but 1% of farms. Rates of technical change shown in Table 15 indicate relative parity across farm sizes (ranging from 3.48% to 3.82%), the exception being the 5-20 ha size class (2.32%). While there may be parity in the technical change estimates across farm sizes, TFP growth declines with size until the largest size class.

The South region has had the second-slowest growth of output, but also the second-

Table 15
Total Factor Productivity Growth Decomposition by Farm Size in the South Region of Brazil, 1985-2006
(percent per year)

Variable	South	Farm Size Class (hectares)				
		0-5	5-20	20-100	100-500	500-
Total factor productivity decomposition[1]						
Technical change	4.06	3.82	2.35	3.48	3.54	3.82
Technical efficiency change	-2.79	-1.64	-1.17	-2.60	-3.07	-2.07
Total factor productivity change	1.27	2.18	1.19	0.88	0.47	1.74
TFP change at 90th percentile	1.76	3.12	1.78	1.69	1.05	2.35
TFP change at 10th percentile	0.73	0.08	0.46	-0.01	-0.31	1.13
Complementary data from 2006						
Output (R$1000s) and size shares[2]	43,926,142	0.07	0.24	0.30	0.18	0.21
Number of farms and size shares[2]	1,006,203	0.23	0.43	0.26	0.05	0.01
Representative farms	2,754	488	603	621	590	414

Notes:

1. All estimates are weighted by output shares.
2. Shares exclude "producer without area," a category that did not exist in previous censuses.
3. In order to achieve convergence, 24 RFs were removed from the 0-5 ha model and 14 RFs were removed from the 5-20 ha model.

slowest growth of inputs. The South's poor performance has been diminished by the poor productive efficiency of the middling class sizes (5-20 ha, 20-100 ha, and 100-500 ha). These class sizes have accounted for 72% of regional output and 74% of regional farms. Yet their respective average annual TFP growth rates have been 1.19%, 0.88%, and 0.47%. Indeed, while TFP growth has declined over the range of these size classes, technical change increased. Output and input growth from Table 3 offer little insight into why average-efficient producers in these size classes have performed so poorly, causing inefficiency to increase with size.

One area of focus may be the wide efficiency dispersion in the region's 100-500 ha size class. This class' most-efficient producers have achieved a TFP growth rate of 3.54%, on average each year. Yet the 90th percentile of producers has only achieved a growth rate of 1.05%. Thus a dominant portion of efficiency losses are within that top efficiency layer, suggesting that only a very small group of producers is achieving high rates of productivity growth. The 20-100 ha size class also has heavy efficiency losses in the top efficiency layer, but to a lesser extent. Identifying potential outlier observations may raise the TFP growth rates presented in Table 15 if efficiency gains are larger than technical change losses from their exclusion.

<u>Center-West region</u>

Brazil's Center-West region is different from its northern and southern regional neighbors. For one, it contained only 6% of national farms, but they operated 32% of national area – both extremes when compared with other regions (Table 1). Surprisingly, the Center-West has only accounted for 18% of national output, on par with that produced from the Brazilian Northeast, and less than what has been produced in the South and Southeast. The Center-West contains a large swathe of the Cerrado biome, the broad savannah which has defined Brazil's

Table 16
Total Factor Productivity Growth Decomposition by Farm Size in the Center-West Region of Brazil, 1985-2006
(percent per year)

Variable	Center-West	Farm Size Class (hectares)				
		0-5	5-20	20-100	100-500	500-
Total factor productivity decomposition[1]						
Technical change	-2.81	2.14	3.36	3.44	1.73	-1.96
Technical efficiency change	4.48	-1.90	-2.76	-2.85	-0.88	3.91
Total factor productivity change	1.67	0.24	0.59	0.58	0.85	1.95
TFP change at 90th percentile	2.07	1.41	1.51	1.38	1.25	2.64
TFP change at 10th percentile	1.21	-2.40	-1.11	-0.53	-0.53	1.17
Complementary data from 2006						
Output (R$1000s) and size shares[2]	28,820,355	0.01	0.02	0.08	0.14	0.74
Number of farms and size shares[2]	317,498	0.09	0.19	0.40	0.19	0.11
Representative farms	1,254	180	268	271	270	267

Notes:

1. All estimates are weighted by output shares.
2. Shares exclude "producer without area," a category that did not exist in previous censuses.
3. In order to achieve convergence, twelve RFs were removed from the regional model, nine RFs were removed from the 0-5 ha model, and one RF was removed from the 100-500 ha model.

agricultural frontier. Farms there have employed University- and Embrapa-developed agricultural technologies and practices to overcome the Cerrado's relatively infertile and acidic soils. In doing so, farms there have been able to exploit scale-dependent machinery to boost production. We think it highly likely that the production technologies employed in a large part of the Center-West differ greatly from those employed outside of the Cerrado biome. Testing such differences is the focus of future research.

The Center-West is widely associated with large farms. Small farms do exist there, although they accounted for a very low proportion of 2006 output (Table 1). Indeed, note in Table 1 that the smallest three size classes in this region accounted for 7% or less of their given size-class' share of national output. Moreover, within the Center-West, together these classes' accounted for only 11% of production. Despite this, farms 100 ha or smaller do account for 68% of all farms within the Center-West.

TFP growth results detailed in Table 16 show relatively poor performance in the smallest four farm-size classes; average annual TFP growth incrementally rises with size from 0.24% in the 0-5 ha class to 0.85% in the 100-500 ha size class. TFP growth then jumps considerably in the largest size class (500-ha) to 1.95%. Muddled by these TFP growth estimates is the unusual result for this region of negative technical change but positive technical efficiency change. Above we had hypothesized the phenomenon as a possible limitation of the model. We now see the odd result is captured within the largest size class, and is only mirrored in the regional results because of this size class' dominant output share (74%), which serve as estimation weights. If we ignore this largest class, thus evaluating 87% of regional producers but only 26% of regional production, we find somewhat low rates of technical change and rates of TFP growth below 1% per annum. The region's seemingly productive use of scale-dependent machinery and the qualitatively different results for the largest size class relative to the other four make drawing general conclusions about the region's productive efficiency difficult.

Also of note in Table 16 is the negative productivity growth estimated for every size class' 10th percentile of producers, except for the largest. Thus the least productive producers across nearly all size classes in this region have been increasingly inefficient, their input growth exceeding their output growth.

Robustness of the results

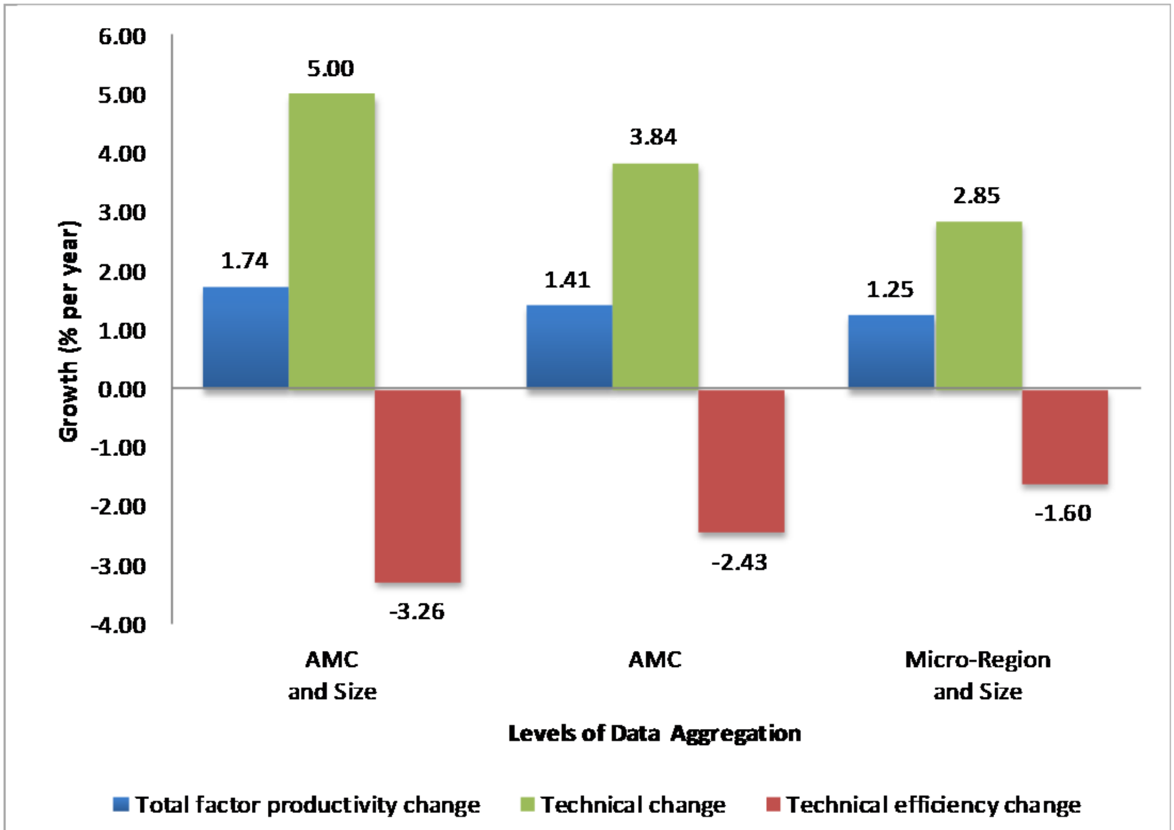
Various sensitivity tests were conducted on the TFP growth rates presented here. Specifically, we tested how a) the data's level of disaggregation, b) screening for outliers, c) accounting for various levels of unobserved heterogeneity, d) an emphasis on 'farm' efficiency rather than 'productive' efficiency, and e) the disaggregation of intermediate inputs may have impacted our estimate of Brazil's agricultural TFP growth.

<u>Data aggregation</u>

We hypothesized above that one reason the present study's TFP results may be slower than those from the literature is because of the data's level of aggregation. The more numerous are the observations, the more likely it is for a few to be driving technical change in a frontier specification, and the more likely it is to have substantial efficiency losses for a large majority. Recall that we employ RFs by size aggregated to the level of AMCs. We thus tested how Brazil's national TFP decomposition estimates from Table 10 and 11 change as the data are incrementally aggregated to higher levels (Figure 1).

As expected, technical change falls considerably as we aggregate, from an average annual rate of 5% using AMC and size aggregations, to 3.84% aggregating to the AMC

Figure 1
Total Factor Productivity Growth in Brazil:
The Influence of Alternative Levels of Data Aggregation
(1985-2006, percent per year)



Notes:
1. All estimates are weighted by output shares.
2. AMC = Minimum Comparable Area.
3. Number of representative farms: AMC and Size, 16,987; AMC, 3,766; Micro-Region and Size, 2,631.

level (thus eliminating the by-farm size disaggregation), to 2.85% aggregating to the micro-region level but maintaining the by-farm size distinction. Surprisingly, though, TFP growth also falls, but by a far smaller proportion than technical change. Therefore, the data's lower level of aggregation does not appear to be why our TFP growth rates differ from those presented in the literature. An alternative hypothesis may be that with multi-output distance frontier specifications there is generally less inefficiency because farms are compared to specific production technologies (e.g. crops and animal products), rather than to an aggregate production technology.

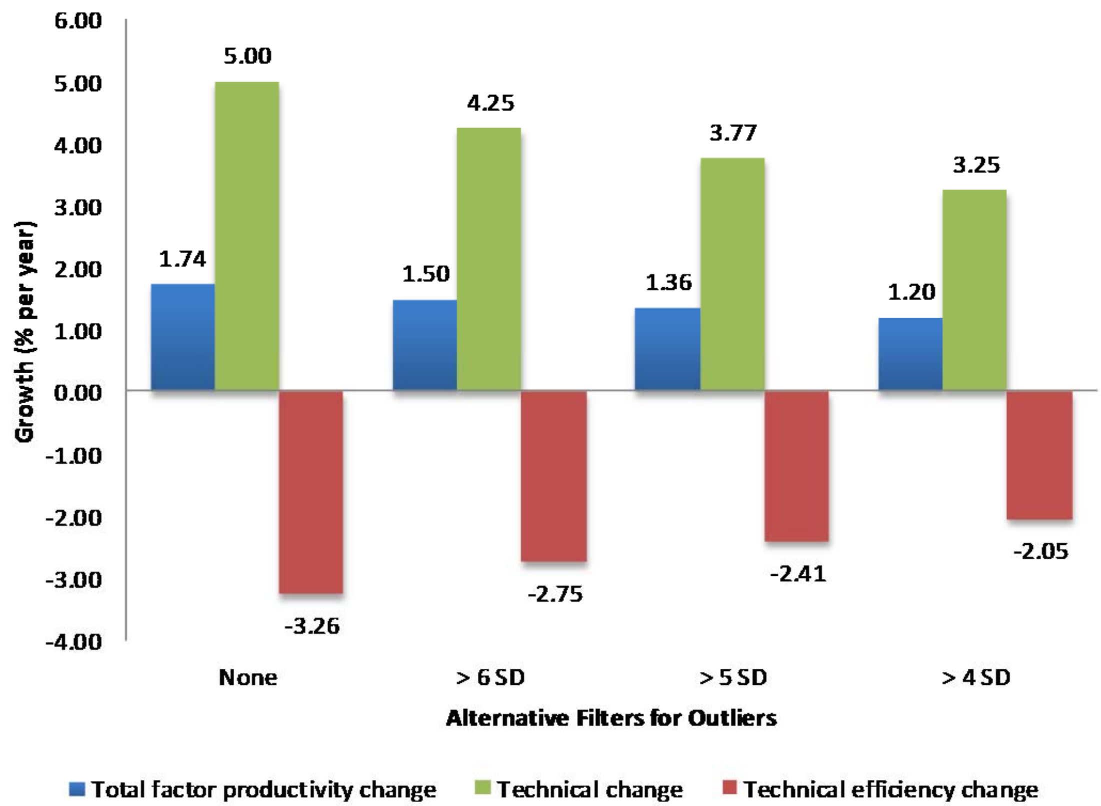
<u>Outliers</u>

Part of having more disaggregated data than previously employed to estimate Brazil's farm productivity is the higher probability of encountering outlier observations. Even with an econometric error in equation (11) to account for idiosyncratic 'noise,' screening for outliers can be difficult. Moreover, their elimination could raise or lower TFP growth, depending on how that observation's omission affects technical and mean-efficiency changes. Indeed, the net effect is an empirical question.

In Figure 2, we test the TFP impact of eliminating more than six, five, and four standard deviations of the econometric error. For simplicity, the outliers were identified with the residuals calculated from an average production function estimated with OLS. Once the extreme observations were identified and removed, the stochastic frontier production function was re-estimated.

As expected, we find that both efficiency losses and technical change decline as more observations are eliminated (Figure 2). What we had not anticipated, though, was that such a small number of extreme observations would be so influential. As such, Brazil's average annual technical change and TFP growth fall substantially as increasing numbers of observations are screened. That eliminating observations which, for any given census year, were more than six standard deviations from the mean error lowers technical change from 5.0% per annum to 4.25% per annum, and TFP growth from 1.74% per annum to 1.5% per annum, was quite surprising. For performance to fall so quickly by eliminating 48 RFs suggests these are

Figure 2
Total Factor Productivity Growth in Brazil:
The Influence of Outliers
(1985-2006, percent per year)



Notes:
1. All estimates are weighted by output shares.
2. SD refers to standard deviations.
3. Number of representative farms: no filter, 16,987; > 6 SD, 16,939; > 5 SD, 16,864; > 4 SD, 16,682.

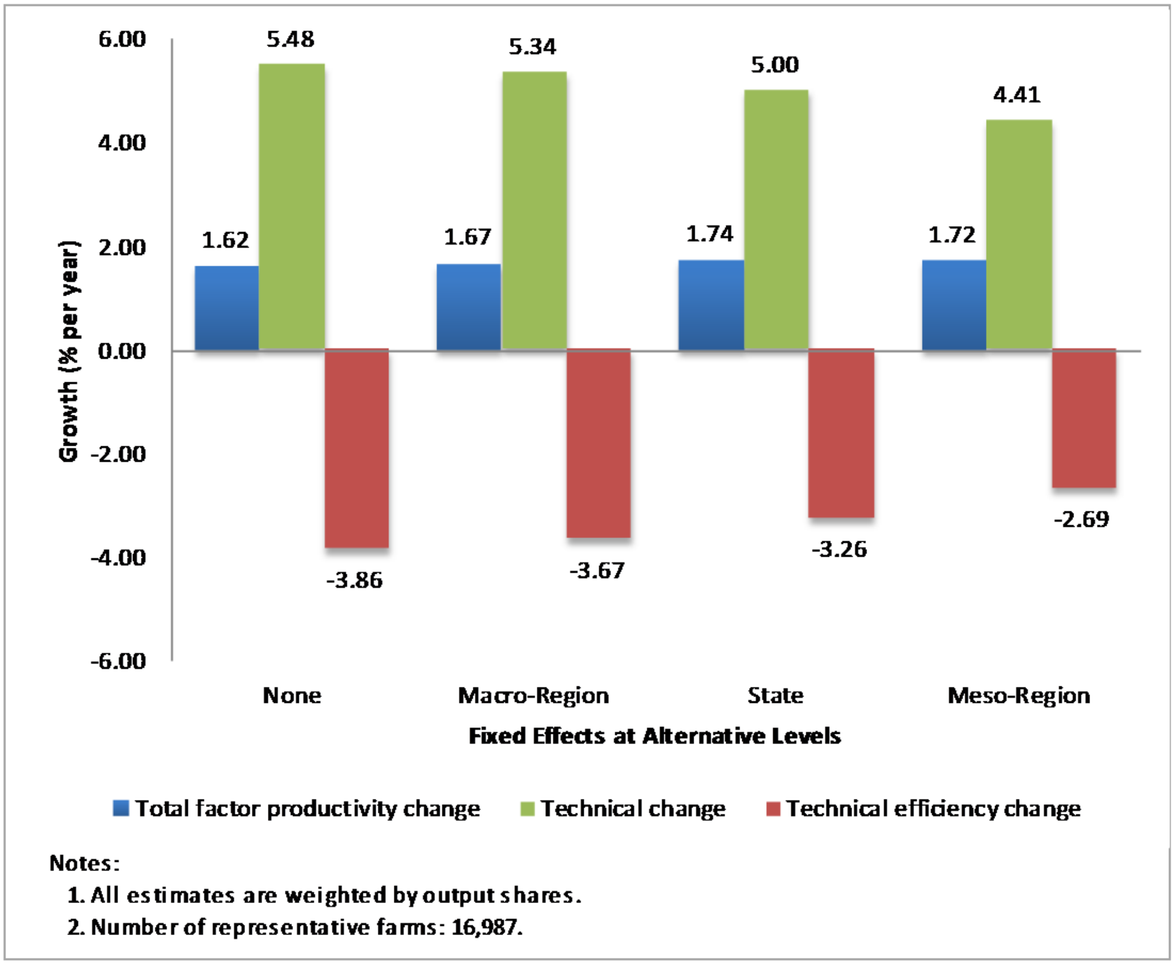
influential observations that need more careful handling. For this reason, the present study presents TFP decomposition estimates which are not filtered for outliers. In future research we will examine this issue in more depth.

Unobserved heterogeneity

We have further questioned the importance of accounting for unobserved heterogeneity when estimating TFP growth. This is a particularly tricky issue when employing frontier specifications because one must be sure that what heterogeneity one does account for is not efficiency related. For example, a farm-level dummy may be intended to capture unobserved heterogeneity relating to soil quality but may actually capture managerial prowess.

We present in Figure 3 the impact on our TFP growth estimates as we vary the level of fixed effects. We move from macro-regions (5) to states (27) to meso-regions (137). The findings are some-what surprising. Technical change declines as more refined levels of fixed effects are modeled. Unlike technical change, TFP growth rises as we move away from state-fixed effects. Thus, as we account for lower levels of unobserved heterogeneity, we observe slower technical change but also less efficiency loss. Because the efficiency losses decline at a slightly faster rate than technical efficiency, TFP growth rises marginally. Note that we did not choose our preferred model based on these results. Agricultural and economic policies do vary by Brazilian state. We thus capture the impact of state policy, leaving more diffuse unobserved heterogeneity (e.g. soil quality) for future research. Indeed, we had intended, and plan for the future, to employ AMC-fixed effects to capture heterogeneity of soils and climate. We were unable to estimate such a model in *xtfrontier,* and are currently exploring other software options.

Figure 3
Total Factor Productivity Growth in Brazil:
The Influence of Unobserved Heterogeneity at Different Levels
(1985-2006, percent per year)



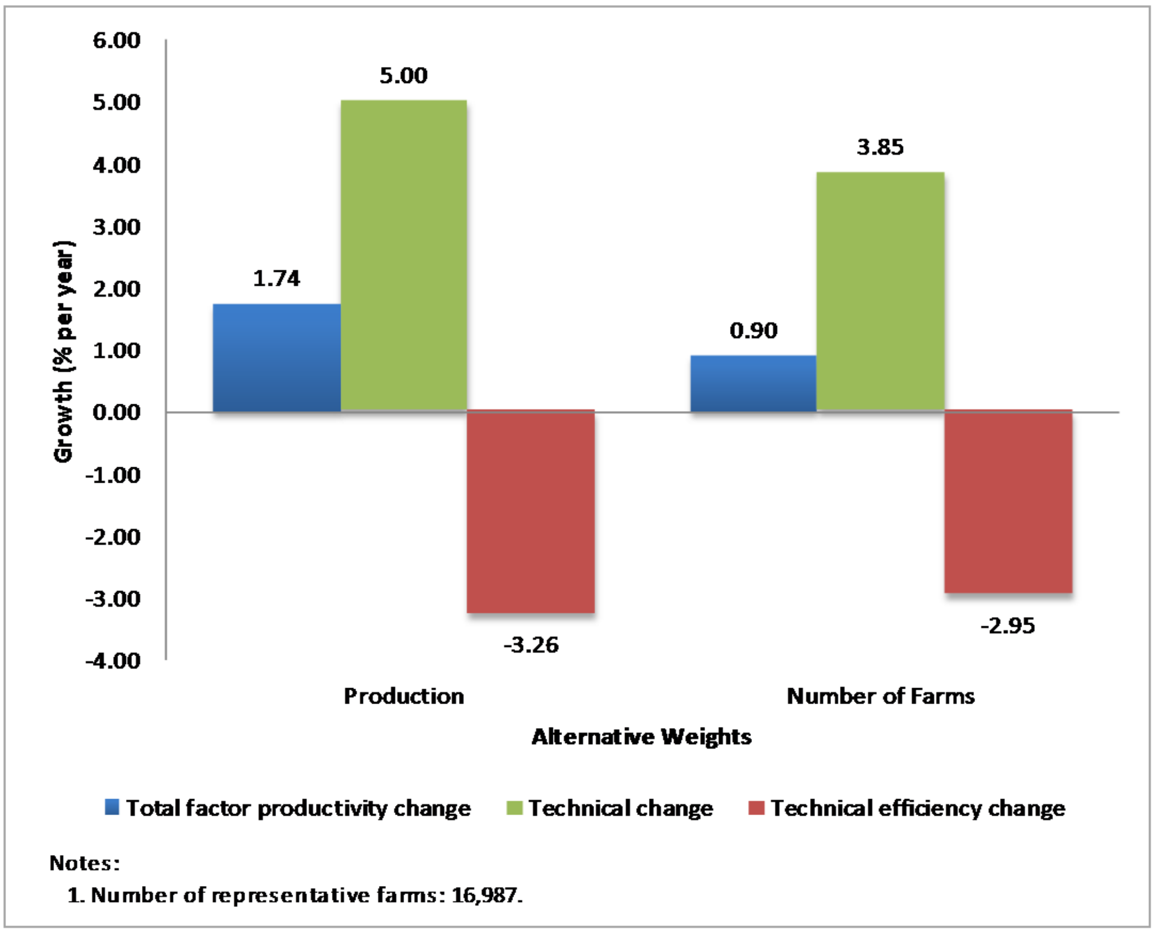
<u>Output versus farm-number estimation weights</u>

When initiating our modeling efforts, we were posed with an important decision with substantial implications: should we weight the data by a given RF's share of output or by its share of farms as we estimate the production technology. The implications of this decision are best seen by referencing Table 1's size shares of regional output and farms. In the Center-West regression, results of which are presented in Table 16, the 500-ha size class accounted for 74% of regional output but only 11% of its farms. Conversely, the 20-100 ha size class accounted for only 8% of regional output but 40% of its farms. A regional regression with output weights attributes significantly more influence to the farms within the 500-ha size class. One with farm weights attributes more influence to the 20-100 ha size class. Recall from Table 16 that the 20-100 ha size class achieved a low 0.58% TFP growth rate, while the 500-ha size class achieved a regional high rate of 1.95%.

Whether one employs output or farm-number weights depends on if the goal is evaluating the efficiency of farms or the efficiency of production. Because we thought estimates based on the efficiency of production would be more comparable to evidence from the literature which employ more aggregated data, we chose the output weights. However, examining 'farm efficiency' is also of interest. Indeed, one might assert that focusing on 'productive efficiency' gives too much influence in the TFP measures to Brazil's large, commercial farmers. As such, government officials might be led to develop policies that may not stimulate innovation or technological change for smallholders. A 'farm efficiency' measure would thus be a more accurate representation of the experience of most farms, and might induce policy more effectively for propelling productivity growth on Brazil's numerous smaller, non-commercial farms. These concerns are diminished, somewhat, when we estimate farms size specific models.

We find a stark difference in national performance between the two weighting schemes (Figure 4). While we evaluate the same RFs, technical change and TFP growth are considerably lower when employing number-of-farm weights. This is an intriguing finding, and a source of future research. It suggests a vision of Brazilian agriculture in which the sector as a whole is quite efficient but most farms are not. Stated differently, where most output is produced TFP has grown at an impressive rate, but this does not reflect the experience of the majority of farms.

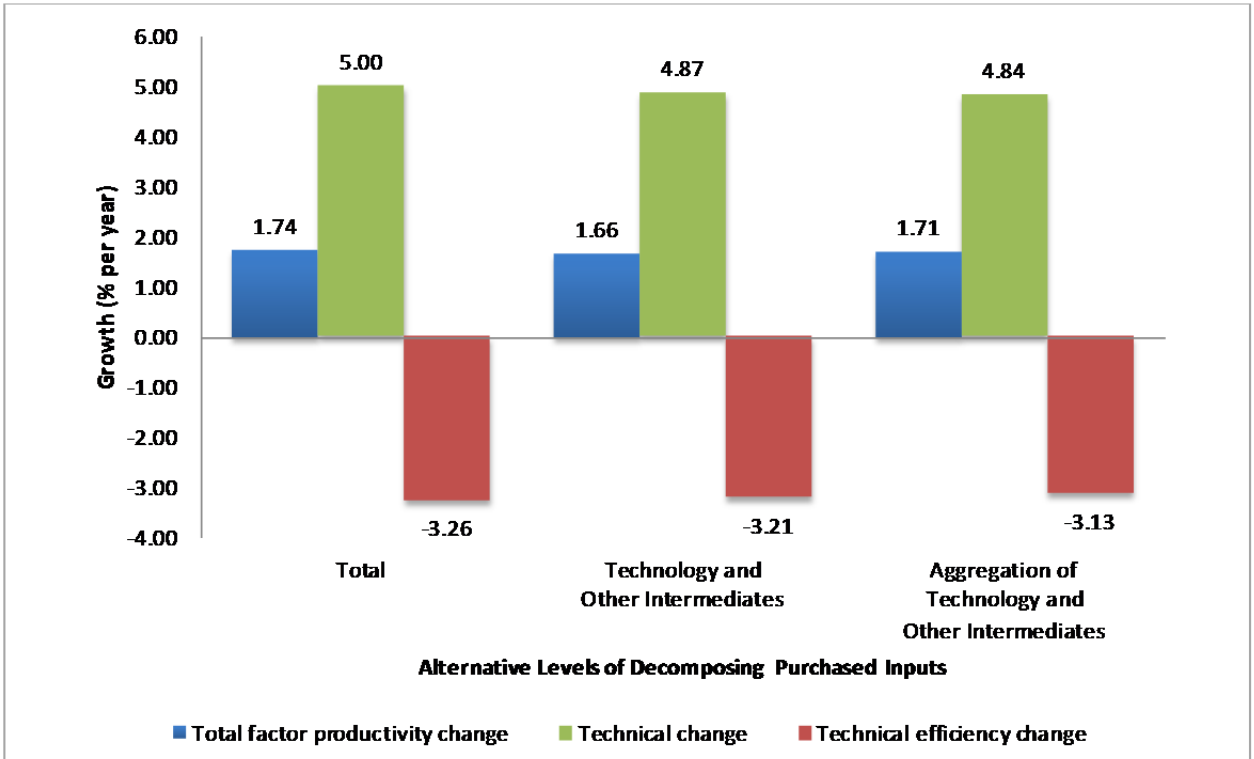
Figure 4
Total Factor Productivity Growth in Brazil:
The Influence of Alternative Weights
(1985-2006, percent per year)



<u>Decomposition of purchased inputs</u>

Lastly we analyzed whether the disaggregation of inputs has a measurable impact on the estimates of TFP growth in Brazil. Figure 5 first shows the original estimates of TFP growth that were presented in Table 10. At the level of Brazil, TFP grew by 1.74% per year between 1985 and 2006. When the inputs were disaggregated into two variables—Technology Intermediates and Other Intermediates—the estimated rate of growth of TFP declines to 1.66% per year. This is not a surprising result, as greater precision in the measurement of inputs explains more of output growth and leaves less of that growth left over to be explained by TFP. However, the disaggregation of the inputs also led to a reduction in the sample size, which could partly explain the decline in the growth of TFP. The sample size declined because of IBGE's data confidentiality protection. Any time there are fewer than three farms in a cell, IBGE presents the data as missing. The disaggregation of purchased inputs increased the number of missing observations in the sample. The last three columns of Figure 5 permit us to determine what share of the decline in TFP was due to disaggregation of purchased inputs and what share was due to the change in sample size. These columns report the results of the model using the sum of purchased inputs, estimated with the sample that was used for the model with Technology and Other Intermediates. When purchased inputs are not disaggregated, but the smaller sample is used, TFP growth falls to 1.71% per year. Thus, a little more than one third of the decline was due to the change in sample size, and nearly two thirds was due to the disaggregation of purchased inputs. In either case, the overall impact on TFP growth is rather small.

Figure 5
Total Factor Productivity Growth in Brazil:
The Influence of Decomposing Purchased Inputs
(1985-2006, percent per year)



Notes:
1. All estimates are weighted by output shares.
2. Number of representative farms: Total, 16,987; Technology and Other Intermediates, 15,718; Aggregation, 15,718.

6. Conclusions and Policy Implications

The present study on Brazil's agricultural total factor productivity growth has found that average annual technical change, and thus the TFP growth of the most-efficient producers, has accelerated at a rather rapid 5% per year, on average, between 1985 and 2006. Yet that pace of growth has not been spread broadly as the majority of producers achieved a far slower productivity growth rate of 1.74%. Considerable production gains could still be achieved if technical efficiency were to grow at a faster rate.

This study also adds a new dimension to the agricultural productivity literature: the by-farm size dimension. The farm sizes achieving, over the 1985-2006 period, the fastest annual average TFP growth were the smallest (0-5 ha) and largest (500- ha), the former having a small growth advantage. Farmers operating less than 5 ha also achieved the fastest rate of technical change. The patterns of farm-size-specific performance in Brazil varied tremendously across regions. In Brazil's North, TFP growth declined with size, in the Center-West it increased with size, and in the South it mirrored the U-shaped national distribution. The TFP-size patterns were less clear cut in the Northeast and Southeast: rising, falling and then rising again. In the Northeast the 5-20 ha class had the highest TFP growth, whereas in the Southeast it was the 500-ha class.

Beyond examining size-TFP trends, policymakers may also be interested in where TFP growth is most sluggish. The slowest TFP growth rate—1.14%—in the national analysis was experienced by the 20-100 ha size class, followed by the 100-500 ha class at 1.29%. Yet this was not true for all regions. In the Northeast, Southeast, and South, the slowest growth was by the 100-500 ha size class. In the North it was the largest farms, and in the Center-West the smallest. There is likely slow TFP growth in the 100-500 ha size class because they have faced various constraints (e.g. credit, knowledge, incentives) to adopting production technologies suitable for their size. When TFP growth for the 100-500 ha class is decomposed, only in the Southeast does the 100-500 ha class achieve the slowest technical change. The limitations in the Northeast and South relate more to the high level of efficiency losses of most producers in this size class.

The findings of this study have a number of important implications for public policies in Brazil. First, TFP growth was led by technical change of the most efficient producers. Average TFP growth was much slower because the majority of producers were unable to match the productivity gains of the most efficient producers. There are a number of policies that can contribute to increasing technical efficiency for many of these producers. Public investment in infrastructure is likely key. Brazilian producers face bottlenecks and high transactions costs due to inadequate public infrastructure investment. Roads, rail transport, and other investments in infrastructure that help to reduce transportation costs can boost technical efficiency and competiveness of Brazilian agriculture.

Second, improvements in extension services may increase technical efficiency and thus TFP growth for a large share of Brazilian producers. Much of the public sector technical assistance infrastructure was dismantled in the early 1990s, and only recently has it once again become a policy priority. Yet it is still woefully inadequate. According to the 2006 agricultural census data, only 22% of farms utilize technical assistance, and less than half of these do so regularly. Roughly half of those 22% of farms access public sector technical assistance. The other half is serviced through cooperatives, contracting industries such as with chicken and pig slaughterhouses, and the private sector. There is clearly scope to improve agricultural extension, in terms of the number of farms reached, the frequency of interactions, and the overall quality of the services.

Finally, an intriguing finding of this study is that TFP growth has been slowest for farms in the middle of the size distribution. TFP only grew by 1.14% per year for farms in the 20-100 ha size class, and by 1.29% per year for farms with 100 to 500 hectares. There are two complementary hypotheses that might explain this lackluster performance. One is that there are technologies that are more suitable to the smallest and largest farms. Large farms, for example, have led the growth process in the Center West where soybeans, corn, and cotton have expanded rapidly in recent decades based on heavy investments in machinery and technology. This has occurred on extremely large farms, often with thousands of hectares of land. A share of the small farms, on the other hand, have done extremely well where they have been able to combine state of the art technology with abundant family labor and overcome the transactions costs associated with accessing input and output markets. Institutions, in the form of contract farming or cooperatives have often played an essential role in these cases of success. Examples can be found with chickens, pigs, and horticulture, just to name a few.

A second hypothesis is that public policy has focused on the small and the large producers and has, to a certain extent, ignored the middle. Policies toward the sector are divided between the Ministry of Agriculture—which focuses on large commercial "agribusiness" enterprises—and the Ministry of Agrarian Development which focuses on "family farms." In order to continue to accelerate TFP growth in Brazil, it should be a high priority—for both research and policy—to identify the obstacles facing mid-sized farms and the policies that could assist them to improve their productivity and competitiveness.

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Appendix Tables

Appendix Table A1
Variation of Outputs and Inputs by Farm Size and Region: 1985-95/96
(percent)

Region/Size (ha)	Output	Land	Family Labor	Purchased Inputs			Capital Stock			
				Technology Intermediates	Other Intermediates	Total	Machines	Animals	Trees	Total
Brazil										
0-5	22	-24	-21	85	44	60	28	7	25	23
5-20	13	-15	-22	79	9	36	15	9	-6	12
20-100	8	-9	-19	49	7	23	4	15	-4	4
100-500	5	-8	-22	31	6	15	2	8	-13	1
500-	34	-3	-16	52	35	40	9	6	-20	7
North										
0-5	47	-25	-22	134	-8	15	192	4	118	61
5-20	21	-25	-31	81	-15	2	50	23	77	50
20-100	13	-13	-22	43	4	22	14	46	132	65
100-500	9	-14	-28	34	2	17	22	46	198	71
500-	26	-2	-17	31	-6	7	14	29	-2	24
Northeast										
0-5	16	-21	-19	57	33	40	128	-9	24	29
5-20	6	-12	-17	77	3	23	61	3	2	24
20-100	-12	-9	-16	35	-20	-6	11	3	-44	-12
100-500	-17	-13	-24	18	-16	-8	-7	-8	-23	-11
500-	20	-19	-25	41	11	18	0	-16	2	-3
Southeast										
0-5	19	-22	-20	42	41	41	17	18	40	21
5-20	5	-16	-23	41	13	24	16	6	2	12
20-100	1	-12	-21	29	20	24	1	11	7	3
100-500	0	-11	-23	32	19	24	-1	4	-16	-4
500-	10	-13	-23	37	47	45	-7	-13	-30	-12
South										
0-5	34	-29	-29	143	70	112	19	49	-25	21
5-20	20	-14	-22	90	0	50	11	12	-33	9
20-100	21	-9	-20	61	-1	32	3	15	-13	3
100-500	16	1	-8	30	-7	9	4	5	-28	3
500-	25	-9	-10	33	31	31	7	-19	34	4
Center-West										
0-5	-3	-60	-56	110	10	40	-13	-6	-38	-13
5-20	8	-26	-41	90	15	36	11	37	-12	14
20-100	38	8	-6	56	20	35	14	41	71	17
100-500	45	6	-12	32	14	24	12	24	43	14
500-	93	11	-3	69	36	57	30	28	7	29

Notes: See Table 2.

Appendix Table A2
Variation of Outputs and Inputs by Farm Size and Region: 1995/96-06
(percent)

Region/Size (ha)	Output	Land	Family Labor	Purchased Inputs			Capital Stock			
				Technology Intermediates	Other Intermediates	Total	Machines	Animals	Trees	Total
Brazil										
0-5	65	-3	-8	-15	64	29	19	16	97	30
5-20	56	4	-12	8	73	40	-7	17	80	5
20-100	41	-1	-12	8	50	30	-25	16	35	-15
100-500	36	-9	-15	95	53	70	-20	6	15	-14
500-	93	-6	23	313	115	176	2	20	-29	3
North										
0-5	36	-28	-8	13	108	65	28	-29	-32	-30
5-20	47	-8	-30	52	68	48	63	42	-21	2
20-100	91	8	-13	138	137	88	42	72	5	27
100-500	77	-1	-21	165	146	100	21	56	-60	-3
500-	103	-9	9	426	224	198	25	67	-20	31
Northeast										
0-5	89	-11	-15	5	93	62	90	-17	216	93
5-20	131	7	-10	3	82	50	54	2	273	102
20-100	79	3	-6	0	67	41	9	1	165	45
100-500	44	-8	-9	19	67	55	-19	-6	49	-1
500-	121	-3	31	608	216	321	0	-12	-31	-7
Southeast										
0-5	50	37	35	-12	45	20	-4	93	30	11
5-20	57	9	-1	48	88	70	-15	39	51	1
20-100	31	-13	-19	5	35	23	-37	11	12	-24
100-500	31	-23	-23	51	39	44	-36	-11	22	-23
500-	80	-11	16	247	82	119	-22	-15	-14	-21
South										
0-5	52	6	5	-15	76	8	13	1	37	12
5-20	32	-5	-19	8	84	17	-12	4	13	-10
20-100	26	-10	-22	20	75	25	-23	0	52	-21
100-500	31	-3	-8	229	85	121	-9	-5	-19	-9
500-	59	-5	53	169	75	85	-1	-15	-80	-5
Center-West										
0-5	91	51	38	34	196	107	1	95	-40	12
5-20	94	69	34	78	152	114	15	101	-30	27
20-100	80	32	19	89	94	82	-12	72	-41	0
100-500	37	-4	-14	112	79	78	-16	32	-80	-10
500-	116	-5	20	466	201	245	19	37	-95	22

Notes: See Table 2.

Appendix Table A3
Weights Used for Capital Components by Macro-Region: 1985

	Macro-Regions				
	North	Northeast	Southeast	South	Center-West
Machines	0.15	0.39	0.50	0.51	0.59
Animals	0.49	0.29	0.23	0.34	0.35
Trees	0.36	0.32	0.27	0.15	0.05

Appendix Table A4
Regressions of Standardized Outputs and Capital Components for Macro-Regions: 1985

North

Source	SS	df	MS			
					Number of obs	886
					F(3, 882)	375.82
Model	454.622711	3	151.540904		Prob > F	0
Residual	355.647676	882	.403228657		R-squared	0.5611
					Adj R-squared	0.5596
Total	810.270386	885	.915559759		Root MSE	0.635

Output	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
Machines	0.1458025	.0434352	3.36	0.001	0.0605540	0.2310509
Animals	0.4669874	.0308696	15.13	0.000	0.4064009	0.5275739
Trees	0.3493142	.0257053	13.59	0.000	0.2988635	0.3997648
_cons	-0.004618	.0215992	-0.21	0.831	-0.0470098	0.0377738

Northeast

Source	SS	df	MS			
					Number of obs	5903
					F(3, 5899)	2659.45
Model	2765.91256	3	921.970854		Prob > F	0
Residual	2045.05208	5899	.346677756		R-squared	0.5749
					Adj R-squared	0.5747
Total	4810.96464	5902	.815141417		Root MSE	0.58879

Output	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
Machines	0.4067861	.0091558	44.43	0.000	0.3888374	0.4247348
Animals	0.3053576	.0081494	37.47	0.000	0.2893818	0.3213335
Trees	0.3302573	.0077534	42.60	0.000	0.3150578	0.3454568
_cons	-0.0194262	.0076681	-2.53	0.011	-0.0344584	-0.004394

Southeast

Source	SS	df	MS			
					Number of obs	6250
					F(3, 6246)	7734.15
Model	4348.77981	3	1449.59327		Prob > F	0
Residual	1170.67251	6246	.187427555		R-squared	0.7879
					Adj R-squared	0.7878
Total	5519.45232	6249	.883253693		Root MSE	0.43293

Output	Coef.	Std. Err.	t	P>t	[95% Conf.	Interval]
Machines	0.603017	.0081848	73.68	0.000	0.5869725	0.6190624
Animals	0.276826	.0070229	39.42	0.000	0.2630587	0.2905934
Trees	0.319051	.0060065	53.12	0.000	0.3072761	0.3308258
_cons	0.032524	.0054965	5.92	0.000	0.0217485	0.0432987

Appendix Table A4 (continued)
Regressions of Standardized Outputs and Capital Components for Macro-Regions: 1985

South

Source	SS	df	MS			Number of obs	2680
						F(3, 2676)	3094.76
Model	1893.0077	3	631.002566			Prob > F	0
Residual	545.619267	2676	.203893597			R-squared	0.7763
						Adj R-squared	0.776
Total	2438.62696	2679	.910275089			Root MSE	0.45155
Output	Coef.	Std. Err.		t	P>t	[95% Conf.	Interval]
Machines	0.6205706	.0116846		53.11	0.000	0.5976589	0.6434823
Animals	0.4116066	.0137318		29.97	0.000	0.3846807	0.4385325
Trees	0.1762664	.0089613		19.67	0.000	0.1586945	0.1938382
_cons	0.0307046	.0087862		3.49	0.000	0.0134762	0.047933

Center-West

Source	SS	df	MS			Number of obs	1178
						F(3, 1174)	2301.34
Model	677.600916	3	225.866972			Prob > F	0
Residual	115.223352	1174	.098145956			R-squared	0.8547
						Adj R-squared	0.8543
Total	792.824268	1177	.673597509			Root MSE	0.31328
Output	Coef.	Std. Err.		t	P>t	[95% Conf.	Interval]
Machines	0.6111205	.0179638		34.02	0.000	0.5758758	0.6463652
Animals	0.3661263	.0145015		25.25	0.000	0.3376745	0.394578
Trees	0.054273	.0096301		5.64	0.000	0.0353788	0.0731672
_cons	0.0100209	.0093259		1.07	0.283	-0.0082763	0.0283182

Appendix Table A5

Stochastic Frontier Analysis, Translog Production Function, FE controlled by States, Weighted by Output

Panel Data for Brazil, 1985, 1995/96, 2006

```
Time-varying decay inefficiency model          Number of obs      =     509
Group variable: pid                            Number of groups   =     169

Time variable: time                            Obs per group: min =
                                                              avg =
                                                              max =

                                              Wald chi2(41)      =  2.50e+1
Log likelihood  = -2.778e+11                   Prob > chi2        =    0.00
```

Y	Coef.	Std. Err.	z	P>z	[95% Conf.	Interval]
A	-0.1457138	8.15e-06	-1.8e+04	0.000	-0.1457298	-0.145698
L	0.7305411	.0000215	3.4e+04	0.000	0.7304989	0.7305833
I	0.8324321	8.78e-06	9.5e+04	0.000	0.8324149	0.8324493
K	-0.1634356	9.86e-06	-1.7e+04	0.000	-0.1634549	-0.163416
T	0.0500321	3.39e-07	1.5e+05	0.000	0.0500315	0.0500328
AA	-0.01373	1.07e-06	-1.3e+04	0.000	-0.0137321	-0.013728
LL	0.1363653	5.12e-06	2.7e+04	0.000	0.1363552	0.1363753
II	-0.051293	1.66e-06	-3.1e+04	0.000	-0.0512963	-0.05129
KK	0.024018	1.70e-06	1.4e+04	0.000	0.0240147	0.0240213
AL	-0.0604651	3.10e-06	-1.9e+04	0.000	-0.0604712	-0.060459
AI	0.046341	1.06e-06	4.4e+04	0.000	0.0463389	0.046343
AK	-0.0111472	1.19e-06	-9341.85	0.000	-0.0111495	-0.011145
LI	-0.0426221	3.14e-06	-1.4e+04	0.000	-0.0426283	-0.042616
LK	-0.0004557	3.21e-06	-142.11	0.000	-0.0004620	-0.000449
IK	0.011856	1.41e-06	8387.12	0.000	0.0118532	0.0118588
_cons	3.233701	.0000461	7.0e+04	0.000	3.2336110	3.233792
/mu	1.117244	.0000104	1.1e+05	0.000	1.1172230	1.117264
/eta	-0.052258	4.38e-07	-1.2e+05	0.000	-0.0522589	-0.052257
/lnsigma2	-0.9145911	3.64e-06	-2.5e+05	0.000	-0.9145982	-0.914584
/ilgtgamma	-0.7105047	.0000132	-5.4e+04	0.000	-0.7105306	-0.710479
sigma2	0.4006804	0.00000146			0.4006776	0.4006833
gamma	0.3294873	0.00000292			0.3294816	0.3294931
sigma_u2	0.1320191	0.00000155			0.1320161	0.1320222
sigma_v2	0.2686613	0.000000825			0.2686597	0.2686629

Appendix Table A6

Stochastic Frontier Analysis, Translog Production Function, FE controlled by States, Weighted by Output

Panel Data for Brazil, Farm Size Class of 0-5ha, 1985, 1995/96, 2006

```
Time-varying decay inefficiency model          Number of obs      =      9174
Group variable: pid                            Number of groups   =      3058

Time variable: time                            Obs per group: min =         3
                                                              avg =         3
                                                              max =         3

                                               Wald chi2(41)      =  4.72e+10
Log likelihood  = -1.805e+10                   Prob > chi2        =    0.0000
```

Y	Coef.	Std. Err.	z	P>z	[95% Conf.	Interval]
A	2.022751	.0001025	2.0e+04	0.000	2.0225500	2.022952
L	0.2422502	.0001761	1375.33	0.000	0.2419050	0.2425955
I	-0.2981131	.0000433	-6884.61	0.000	-0.2981979	-0.2980282
K	0.4647692	.0000368	1.3e+04	0.000	0.4646970	0.4648414
T	0.0705105	1.57e-06	4.5e+04	0.000	0.0705074	0.0705136
AA	0.048749	.0000312	1562.67	0.000	0.0486878	0.0488101
LL	0.1063937	.0001275	834.73	0.000	0.1061439	0.1066435
II	0.1250972	7.43e-06	1.7e+04	0.000	0.1250826	0.1251118
KK	-0.0102685	6.20e-06	-1655.15	0.000	-0.0102806	-0.0102563
AL	-0.6843102	.0000559	-1.2e+04	0.000	-0.6844197	-0.6842007
AI	-0.0833326	.0000146	-5721.15	0.000	-0.0833611	-0.083304
AK	-0.1543671	.0000138	-1.1e+04	0.000	-0.1543942	-0.1543401
LI	0.1419563	.0000251	5650.80	0.000	0.1419071	0.1420056
LK	-0.0977291	.0000214	-4565.42	0.000	-0.0977710	-0.0976871
IK	-0.0159507	5.89e-06	-2706.05	0.000	-0.0159622	-0.0159391
_cons	4.749861	.0002241	2.1e+04	0.000	4.7494220	4.7503
/mu	1.462547	.0000479	30501.63	0.000	1.4624530	1.462641
/eta	-0.0589412	1.57e-06	-3.7e+04	0.000	-0.0589442	-0.0589381
/lnsigma2	-0.607943	.000016	-3.8e+04	0.000	-0.6079743	-0.6079118
/ilgtgamma	-0.3272463	.0000465	-7041.47	0.000	-0.3273374	-0.3271552
sigma2	0.5444697	0.00000869			0.5444526	0.5444867
gamma	0.4189108	0.0000113			0.4188886	0.418933
sigma_u2	0.2280842	0.00000921			0.2280662	0.2281023
sigma_v2	0.3163854	0.00000409			0.3163774	0.3163935

Appendix Table A7

Stochastic Frontier Analysis, Translog Production Function, FE controlled by States, Weighted by Output

Panel Data for Brazil, Farm Size Class of 5-20ha, 1985, 1995/96, 2006

```
Time-varying decay inefficiency model          Number of obs      =     11157
Group variable: pid                            Number of groups   =      3719

Time variable: time                            Obs per group: min =         3
                                                              avg =         3
                                                              max =         3

                                               Wald chi2(41)      =  9.92e+10
Log likelihood  = -3.675e+10                   Prob > chi2        =    0.0000
```

Y	Coef.	Std. Err.	z	P>z	[95% Conf.	Interval]
A	-5.7227050	.0006543	-8745.76	0.000	-5.7239870	-5.721422
L	-1.8242500	.0003035	-6011.04	0.000	-1.8248450	-1.823655
I	0.2000372	.0000831	2407.56	0.000	0.1998743	0.2002
K	0.7113639	.0000773	9207.13	0.000	0.7112125	0.7115154
T	0.0456873	7.36e-07	6.2e+04	0.000	0.0456858	0.0456887
AA	3.1074680	.000264	1.2e+04	0.000	3.1069510	3.107985
LL	0.5521628	.0000673	8198.54	0.000	0.5520308	0.5522948
II	-0.0387869	6.02e-06	-6443.96	0.000	-0.0387987	-0.0387751
KK	-0.0784369	5.45e-06	-1.4e+04	0.000	-0.0784476	-0.0784262
AL	0.4019225	.0001179	3408.62	0.000	0.4016914	0.4021536
AI	-0.0457236	.0000331	-1379.98	0.000	-0.0457885	-0.0456586
AK	-0.2647076	.0000312	-8474.40	0.000	-0.2647688	-0.2646464
LI	0.0316462	.0000171	1846.48	0.000	0.0316126	0.0316798
LK	0.0221246	.0000161	1376.15	0.000	0.0220931	0.0221561
IK	0.0856119	5.14e-06	1.7e+04	0.000	0.0856018	0.085622
_cons	10.9125300	.0009156	1.2e+04	0.000	10.9107400	10.91433
/mu	0.9597692	.0000214	44911.35	0.000	0.9597273	0.9598111
/eta	-0.0576249	1.08e-06	-5.3e+04	0.000	-0.0576270	-0.0576228
/lnsigma2	-1.0389450	.0000104	-1.0e+05	0.000	-1.0389650	-1.038925
/ilgtgamma	-0.4556897	.0000325	-1.4e+04	0.000	-0.4557535	-0.455626
sigma2	0.3538277	0.00000369			0.3538205	0.353835
gamma	0.3880088	0.00000772			0.3879937	0.388024
sigma_u2	0.1372883	0.00000394			0.1372806	0.137296
sigma_v2	0.2165395	0.00000176			0.2165360	0.2165429

Appendix Table A8

Stochastic Frontier Analysis, Translog Production Function, FE controlled by States, Weighted by Output

Panel Data for Brazil, Farm Size Class of 20-100ha, 1985, 1995/96, 2006

```
Time-varying decay inefficiency model           Number of obs      =     11214
Group variable: pid                             Number of groups   =      3738

Time variable: time                             Obs per group: min =         3
                                                               avg =         3
                                                               max =         3

                                                Wald chi2(41)      =  2.68e+11
Log likelihood  = -4.828e+10                    Prob > chi2        =    0.0000
```

Y	Coef.	Std. Err.	z	P>z	[95% Conf.	Interval]
A	-1.2387160	.000314	-3944.95	0.000	-1.2393320	-1.238101
L	-0.9197969	.0002845	-3233.22	0.000	-0.9203544	-0.9192393
I	0.0552142	.0000932	592.61	0.000	0.0550316	0.0553968
K	0.3955287	.0000829	4772.48	0.000	0.3953663	0.3956912
T	0.0375622	4.88e-07	7.7e+04	0.000	0.0375612	0.0375631
AA	0.3610403	.0000731	4939.49	0.000	0.3608971	0.3611836
LL	0.661701	.0000488	1.4e+04	0.000	0.6616053	0.6617967
II	-0.0816789	4.84e-06	-1.7e+04	0.000	-0.0816883	-0.0816694
KK	-0.0395911	4.30e-06	-9199.46	0.000	-0.0395995	-0.0395826
AL	0.3110347	.0000615	5059.68	0.000	0.3109143	0.3111552
AI	0.1431927	.0000213	6721.49	0.000	0.1431509	0.1432344
AK	-0.2048069	.0000193	-1.1e+04	0.000	-0.2048447	-0.2047692
LI	-0.1689172	.0000123	-1.4e+04	0.000	-0.1689412	-0.1688931
LK	0.0772379	.0000111	6963.46	0.000	0.0772162	0.0772597
IK	0.0927428	4.16e-06	2.2e+04	0.000	0.0927347	0.092751
_cons	7.623637	.0007962	9574.55	0.000	7.6220770	7.625198
/mu	0.8285968	.000014	58977.82	0.000	0.8285692	0.8286243
/eta	-0.0595315	8.55e-07	-7.0e+04	0.000	-0.0595332	-0.0595298
/lnsigma2	-1.36932	7.91e-06	-1.7e+05	0.000	-1.3693350	-1.369304
/ilgtgamma	-0.5009497	.0000254	-2.0e+04	0.000	-0.5009995	-0.5008998
sigma2	0.2542799	0.00000201			0.2542759	0.2542838
gamma	0.3773175	0.00000598			0.3773058	0.3773292
sigma_u2	0.0959442	0.00000215			0.0959400	0.0959485
sigma_v2	0.1583356	0.000000994			0.1583337	0.1583376

Appendix Table A9

Stochastic Frontier Analysis, Translog Production Function, FE controlled by States, Weighted by Output

Panel Data for Brazil, Farm Size Class of 100-500ha, 1985, 1995/96, 2006

```
Time-varying decay inefficiency model          Number of obs      =     10974
Group variable: pid                            Number of groups   =      3658

Time variable: time                            Obs per group: min =         3
                                                              avg =         3
                                                              max =         3

                                               Wald chi2(41)      =  2.01e+11
Log likelihood  = -6.530e+10                   Prob > chi2        =    0.0000
```

Y	Coef.	Std. Err.	z	P>z	[95% Conf.	Interval]
A	-4.2983890	.0004186	-1.0e+04	0.000	-4.2992090	-4.297569
L	0.2196142	.0003085	711.85	0.000	0.2190096	0.2202189
I	1.720228	.0001229	1.4e+04	0.000	1.7199870	1.720469
K	-1.433975	.0001306	-1.1e+04	0.000	-1.4342300	-1.433719
T	0.0511751	7.21e-07	7.1e+04	0.000	0.0511737	0.0511765
AA	0.9678229	.0000868	1.1e+04	0.000	0.9676527	0.9679931
LL	0.0507095	.0000278	1825.43	0.000	0.0506551	0.050764
II	-0.1569201	4.59e-06	-3.4e+04	0.000	-0.1569291	-0.1569111
KK	0.0530429	5.75e-06	9220.47	0.000	0.0530316	0.0530542
AL	0.0798518	.0000563	1418.76	0.000	0.0797415	0.0799621
AI	-0.0651292	.0000225	-2897.45	0.000	-0.0651733	-0.0650851
AK	0.0180657	.0000243	743.09	0.000	0.0180181	0.0181134
LI	-0.074096	.0000108	-6886.34	0.000	-0.0741171	-0.0740749
LK	0.0202245	.0000116	1746.81	0.000	0.0202019	0.0202472
IK	0.0897547	4.69e-06	1.9e+04	0.000	0.0897455	0.0897639
_cons	15.69417	.0011991	1.3e+04	0.000	15.6918200	15.69652
/mu	1.240861	.0000213	58185.94	0.000	1.2408190	1.240903
/eta	-0.0575723	8.14e-07	-7.1e+04	0.000	-0.0575739	-0.0575707
/lnsigma2	-0.8834228	7.44e-06	-1.2e+05	0.000	-0.8834374	-0.8834083
/ilgtgamma	-0.6760843	.0000267	-2.5e+04	0.000	-0.6761367	-0.6760318
sigma2	0.4133656	0.00000308			0.4133596	0.4133716
gamma	0.3371358	0.00000598			0.3371241	0.3371475
sigma_u2	0.1393603	0.00000329			0.1393539	0.1393668
sigma_v2	0.2740053	0.00000175			0.2740018	0.2740087

Appendix Table A10

Stochastic Frontier Analysis, Translog Production Function, FE controlled by States, Weighted by Output

Panel Data for Brazil, Farm Size Class of 500ha-, 1985, 1995/96, 2006

```
Time-varying decay inefficiency model          Number of obs      =      8442
Group variable: pid                            Number of groups   =      2814

Time variable: time                            Obs per group: min =         3
                                                              avg =         3
                                                              max =         3

                                               Wald chi2(41)      =  3.14e+11
Log likelihood  = -9.231e+10                   Prob > chi2        =    0.0000
```

Y	Coef.	Std. Err.	z	P>z	[95% Conf.	Interval]
A	0.0129424	.0000664	194.93	0.000	0.0128123	0.0130726
L	1.184917	.0000533	2.2e+04	0.000	1.1848130	1.185022
I	0.9752402	.0000292	3.3e+04	0.000	0.9751829	0.9752975
K	0.3754134	.0000355	1.1e+04	0.000	0.3753437	0.375483
T	0.049406	7.30e-07	6.8e+04	0.000	0.0494046	0.0494074
AA	-0.1349779	7.55e-06	-1.8e+04	0.000	-0.1349928	-0.1349631
LL	0.0876712	6.14e-06	1.4e+04	0.000	0.0876592	0.0876833
II	-0.0709756	2.54e-06	-2.8e+04	0.000	-0.0709806	-0.0709707
KK	0.0539401	2.69e-06	2.0e+04	0.000	0.0539348	0.0539453
AL	-0.1786725	7.53e-06	-2.4e+04	0.000	-0.1786872	-0.1786577
AI	0.1429466	3.63e-06	3.9e+04	0.000	0.1429395	0.1429538
AK	-0.0414438	4.94e-06	-8392.61	0.000	-0.0414534	-0.0414341
LI	-0.0373655	4.05e-06	-9229.42	0.000	-0.0373734	-0.0373575
LK	0.0370596	4.07e-06	9098.61	0.000	0.0370517	0.0370676
IK	-0.0423856	2.34e-06	-1.8e+04	0.000	-0.0423902	-0.042381
_cons	-2.201843	.0003409	-6459.83	0.000	-2.2025110	-2.201175
/mu	0.888801	.0000239	37133.79	0.000	0.8887541	0.8888479
/eta	-0.0527353	1.23e-06	-4.3e+04	0.000	-0.0527377	-0.0527329
/lnsigma2	-0.896527	6.48e-06	-1.4e+05	0.000	-0.8965397	-0.8965143
/ilgtgamma	-1.198088	.000033	-3.6e+04	0.000	-1.1981520	-1.198023
sigma2	0.4079841	0.00000264			0.4079790	0.4079893
gamma	0.2318156	0.00000587			0.2318041	0.2318271
sigma_u2	0.0945771	0.00000286			0.0945715	0.0945827
sigma_v2	0.3134071	0.00000172			0.3134037	0.3134104