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ASSESSING BRAZIL’S *CERRADO* AGRICULTURAL MIRACLE: AN UPTADE [1]

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ABSTRACT: Brazil’s emergence as a primary global agricultural producer is often credited to production expansion into soils of the Brazilian savannah or *Cerrado*. These soils are, however, deficient in important nutrients and prone to degradation, requiring input-intensive processes that suggest a low level of productive efficiency. Employing a sequence of agricultural censuses and a biome approach for characterizing agricultural zones, the present study evaluates the Cerrado’s total factor productivity growth and productive potential. The analysis highlights the resource cost of Brazil’s “Cerrado Miracle,” the role of paved road infrastructure in expanding production opportunities, and the significant production gains that the Cerrado may yet achieve. Results suggest a substantial productivity gap between the Cerrado’s most efficient and average producers, implying that Cerrado production might well be further boosted if average producers succeed in adopting the technologies and management practices of the more efficient operators. More generally, and to the extent the Cerrado model is generalizable elsewhere, agricultural development of the world’s savannahs, such as sub-Saharan Africa’s Guinea regions, into breadbaskets will be expensive in terms of material inputs such as fertilizers and pesticides, depending for their success therefore on the real prices of these inputs.

Keywords: Brazilian biomes, Cerrado, total factor productivity, technical change, efficiency change

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RESUMO: O aparecimento do Brasil como um importante produtor agrícola mundial é muitas vezes creditado a expansão da produção para solos da savana brasileira ou Cerrado. Estes solos são, no entanto, deficientes em nutrientes importantes e propensos à degradação, necessitando de processos insumo-intensivos que sugerem um baixo nível de eficiência produtiva. Empregando uma seqüência de Censos agrícolas e uma abordagem de bioma para a caracterização de zonas agrícolas, o presente estudo avalia o crescimento da produtividade total de fatores do Cerrado e do seu potencial produtivo. A análise destaca o custo em termos de recursos do "Milagre do Cerrado" no Brasil, o papel da infra-estrutura rodoviária pavimentada em expandir as oportunidades de produção e os ganhos de produtividade significativos que o Cerrado ainda pode alcançar. Os resultados sugerem uma diferença substancial de produtividade entre os produtores mais eficientes e a média do Cerrado, o que implica que a produção pode ser fortemente aumentada se os produtores médios adotarem com sucesso as tecnologias e práticas de gestão dos produtores mais eficientes. De modo geral, e na medida que modelo do Cerrado seja generalizável em outros locais, o desenvolvimento agrícola de savanas do mundo, tais como as regiões sub-saharianas da Guiné africana, em "celeiros" vai ser caro em termos de insumos tais como fertilizantes e pesticidas, o que torna o seu sucesso, portanto, dependente dos preços reais desses insumos.

Palavras-Chave: biomas brasileiros, Cerrado, produtividade total dos fatores, mudança técnica, mudança de eficiência

1. Introduction

The Food and Agricultural Organization (FAO) estimates that global food production would, by mid-century, need to rise 60% to feed an additional 2 billion people (FAO, 2012). FAO has expressed cautious optimism when saying that such a boost likely would require incorporating more hectares of arable land, pointing to sub-Saharan Africa and Latin America as potential sources of farmland expansion. That optimism may in part be driven by Brazil's successful agricultural transformation of its broad savannah, the Cerrado. Some analysts now consider some of the world's other savannah regions, including sub-Saharan Africa's vast Guinea Savannah, to have the potential to become new breadbaskets, in part because of the agro-climatic characteristics they share with the Brazilian Cerrado (MORRIS et al., 2012).

Brazil's agricultural ascendance into the global market is often credited to production expansion into the Brazilian Cerrado (THE ECONOMIST, 2010; THE NEW YORK TIMES, 2007). Yet these soils are made up primarily of oxisols (46%) and ultisols (15%), weathered soils deficient in important nutrients such as nitrogen, phosphorus, and potassium (LOPES, 1996). Indeed, these tropical soils are characterized by good physical structure but low fertility, high acidity, and a proneness to degradation (THOMAS and AYARZA, 1999). Overcoming such obstacles, Brazilian farmers have employed improved management practices and Embrapa- and university-developed modified crops and grasses (for pasture) to improve the Cerrado biome's productive capacity. For example, Brazil was in 2006 the second-largest global producer of soybeans (FAO, 2011), 48.7% of that coming from the Cerrado.

Farms in the Cerrado, often considered the frontier of Brazilian agriculture, rely on material inputs to ensure that farm technologies thrive in the biome's acidic soils. But as new policy assessments look to the Cerrado as a potential model for transforming other savannahs (MORRIS et al., 2012; WORLD BANK, 2009), it is imperative that we understand the resource cost of such transformations. The Guinea Savannah in particular stretches across 400 million hectares of arable land in sub-Saharan Africa; yet less than 10% of it is cropped (WORLD BANK, 2009). Successfully adapting Brazilian agricultural technologies may provide one key to expanding and improving its output, especially in Mozambique, Nigeria, and Zambia, where for each the Guinea Savannah accounts for a minimum of 63% of total land area (WORLD BANK, 2009). Morris et al. (2012) and the World Bank (2009) have examined the success of the Cerrado transformation and the policy challenges facing the Guinea Savannah. The present study instead focuses on providing an economic evaluation of the Cerrado's agriculture, indicating its resource costs and how the productivity gap between the Cerrado's most-efficient and average producers provides an opportunity for expanding the Cerrado's agricultural potential.

Our hypothesis is that the Cerrado's soils require significant investments in the material inputs needed to, for example, improve nutrient composition enough to allow commercial exploitation. Taken on its own account, that fact is a drag on productive efficiency. The input-intensive nature of the biome's production processes, the substantial distances most material inputs must travel, and the sparseness of paved highways, are reasons to suspect the Cerrado of low productivity growth. If Cerrado producers have indeed operated at low productive efficiency, any significant output-price drop or input-price spike likely would reduce farm profitability and threaten Brazil's position as a globally competitive agricultural supplier. Employing Brazilian agricultural census data (1985, 1995/6, 2006) and environmental rather than political boundaries, the present article explores the resource cost of agricultural production in a savannah of low nutrient quality, focusing on the role of infrastructure in expanding the technological frontier.

Results indicate that annual factor productivity growth among the Cerrado's most efficient producers has been slightly more rapid in the livestock than in the crop sub-sectors of the agricultural economy. Paved-road infrastructure investments have significantly affected crop and livestock productivity growth of the Cerrado's most efficient farms; a 1% improvement in paved-road density raises crop production by 0.86% and livestock production by 0.91%. However, the high resource cost of savannah production is clear. The average farm was, between 1985 and 2006, unable to keep pace with the most-efficient producers, achieving a total factor productivity (TFP) growth rate of only 0.4% per annum. Such high resource cost translates into a sizeable TFP gap between most-efficient and average farmer which, if closed, would substantially boost Brazil's international position as a globally competitive supplier of agricultural commodities.

2. A Biome Assessment of Brazil's Productive Efficiency

Evaluations of Brazil's agricultural performance have focused predominately on measuring total factor productivity (TFP) growth and on comparing growth rates across such political boundaries as states or regions (AVILA et al., 2013; RADA and BUCCOLA, 2012; GASQUES et al., 2010; PEREIRA et al., 2002; and AVILA and EVENSON, 1995). Of these studies, only Avila et al. (2013) and Avila and Evenson (1995) have reported TFP growth rates beyond political boundaries. The former evaluates productivity by ecosystem and biome and the latter by agro-ecological zone. Each provides an assessment of productivity by environmental boundary, although their levels of aggregations vary. For instance, Brazil has 8 ecosystems and 6 biomes but 92 agro-ecological zones, too many for concise result reporting. Indeed, Avila and Evenson (1995) reported TFP growth estimates for only 22 of them.

The Brazilian savannah extends across every Brazilian region and 11 of the 27 states (Fig. 1). Hence, any analysis focusing on political boundaries obscures the agricultural performance and productive potential of the Cerrado itself. In evaluating the Cerrado, the present article evaluates agricultural TFP by Brazilian biome, providing an improved understanding of the productive efficiency of Brazil's most important macro-ecosystem. A biome approach is not uncommon in the environmental literature (KLINK and MACHADO, 2005; RATTER et al., 1997) but is new to productivity estimation in the economics literature. Apart from Avila et al. (2013), Castro de Rezende (2003) and Barros et al (2007) provide the only other known economic analyses focusing strictly on the Cerrado. The former is a land market analysis, the latter an assessment of the Cerrado's competitive agricultural potential. Both define the Cerrado by political boundaries. Moreover, Barros et al (2007) define the Cerrado differently in the same report, alternating between using the Center-West states and the states of Goiás, Minas Gerais, and Mato Grosso. Unfortunately also, all these states contain biomes other than the Cerrado's, and the Cerrado biome itself extends into seven other Brazilian states.

2.1 Brazilian Biomes

Brazil may be divided into six biomes: Amazônia, Cerrado, Pantanal, Caatinga, Mata Atlântica, and Pampa (Fig. 1) (IBGE, 2006). Biome classifications are unique in that they express the environmental conditions which enable flora and fauna to inhabit the given area. The primary objective of the present analysis is to isolate and evaluate farm productivity in the Cerrado biome. For comparison, the Pantanal and Amazônia biomes are grouped together to form a Western biome, and the Pampa, Caatinga, and Mata Atlântica biomes to form an Eastern biome.

The Amazônia biome is the largest in Brazil, accounting for 49.3% of the nation's total area (PORTAL BRASIL, 2011). Covering five states, it may be generally classified as a tropical rainforest with a hot and humid climate, heavy rainfall, and highly acidic soils of low fertility and drainage. The Pantanal biome borders the Amazônia on one side, spans two states, and is characterized as temperate grasslands with long-term flooding. These two biomes together cover 51.1% of Brazil's land area yet, over the 1985 – 2006 period, generated only 6% of its mean total production value.

The Cerrado biome is Brazil's second largest, accounting for 23.9% of the nation's area (PORTAL BRASIL, 2011). Crossing 11 states, it contains the source of three major river basins, has a hot sub-humid tropical climate, distinct wet and dry seasons, and consists of tropical grasslands and savannah whose acidic soils are relatively infertile. As farm expansion into this biome accelerated, so did its share of total farm revenue, rising from 19.2% in 1985, to 28.7% in 1995/6, and to 33.2% in the 2006 census period. As shown in Fig. 2, 1985 – 2006 mean production shares in the Cerrado are greatest for cotton (48.8%), oranges (41.7%), soybeans (39.6%), cattle (37.0%), and sugar (32.0%).

The Eastern biome – Caatinga, Mata Atlântica, and Pampa – is slightly larger than the Cerrado, accounting for 25% of Brazil's land (Fig. 1).

The Caatinga extends over ten states and is a tropical scrub forest of deciduous vegetation and two distinct dry seasons prone to drought. The Mata Atlântica, or Atlantic Forest, biome stretches over 15 states comprised of hot, humid, tropical deciduous forest. The Pampa biome, present only in the state of Rio Grande do Sul, is classified as a steppe and extends into Uruguay and Argentina. It has rainy weather and no dry season; grasses and shrubs are the primary vegetation. Although the Eastern biome covers only one-quarter of Brazil, it accounts for a mean 65.5% of total crop revenue and 34.5% of total livestock revenue over the sample time period. As shown in Fig. 2, the Eastern biome has produced, on average, a minimum 48% of all commodities reported over the three census periods.

2.2 Transportation Infrastructure Investments

Concern about Brazil's transportation infrastructure and its impact on farm production and profitability, especially in the Cerrado, have been widespread (VERA-DIAZ et al., 2009; COSTA and ROSSON, 2007; MATTHEY et al., 2004; SCHNEPF et al., 2001). The most vital form of Brazilian farm transportation is the road system. Matthey et al., (2004) found farm transportation costs in the state of Mato Grosso highest if commodities traveled by truck; yet 62% of farm products are shipped in this manner. Caixeta-Filho and Gameiro (2001) note that greater than 95% of the Cerrado biome's export-destined cotton production is transported by truck to Brazil's southern ports. And an estimated 60% of soybeans and 81% of total farm production are road-transported from this biome (ANUT, 2008).

Because careful farm management techniques and material input use are required in order for the Cerrado's soils to be productive, farms there must thus rely on roads to not only send outputs to market but to obtain the large volume of necessary inputs. And the importance of material inputs to the Cerrado has been great, its share of national material expenditures rising from 23% in 1985 to 25.8% in 1995/6, then leaping to 43.7%

in 2006.[1] Indeed, by 2006 the Cerrado biome accounted for 49.2% of Brazil's fertilizer expenditures and 48% of its pesticide expenditures. And Brazil that year was globally the seventh-largest user of nitrogen fertilizer, fourth-largest user of phosphate fertilizer, and third-largest user of potash fertilizer (FAO, 2011).

3. Measuring TFP Growth

Total factor productivity is generally defined in accounting terms, namely the ratio of an aggregate of total outputs to an aggregate of total conventional inputs and hence the efficiency with which inputs are transformed into outputs. As such, agricultural total factor productivity reflects the total conventional resource cost of farm production. For this purpose, TFP is preferable to other partial-productivity measures, such as yield per hectare (land productivity) or output per worker (labor productivity), because such partial measures account for only a single production factor, whereas TFP accounts for the contributions of all measurable inputs, principally land, labor, capital, and materials. While growth in labor or land productivity may be attributed to rising use of other – less easily observed – inputs, TFP growth reflects improvements in the efficiency of the aggregate conventional input bundle.

While TFP accounting measures have the benefit of providing statistics for each sample year, they are ratios that do not account for random—or stochastic—processes. Modeling agricultural TFP in a stochastic framework is important because agriculture is inherently random, a phenomenon captured with an econometric error term. Nor do accounting measures permit an assessment of productivity growth's variation across producers, such as a decomposition of TFP growth into the performances of its most-efficient and average-efficient producers. One approach to measuring TFP which satisfies these concerns is the stochastic distance frontier. The stochastic portion accounts for agriculture's random processes, the distance portion permits modeling more than one aggregate output grouping (e.g. crops and livestock), and the frontier portion allows separate TFP growth measurement of the most efficient and of average farms as well as of the TFP gap separating them. As such, the stochastic distance frontier provides useful information about the contributions of selected subsectors and farms in total factor productivity growth. The reader is referred to Rada and Buccola (2012) for a diagrammatic understanding of TFP measurement by way of a stochastic input distance frontier.

3.1 Stochastic Input Distance Frontier

A stochastic input frontier, along a ray from the origin, specifies an observation's distance to its production possibilities frontier and is measured as the composite error term (AIGNER et al., 1977; MEEUSEN and van den BROECK, 1977)

$$D_I(x_{kit},\ y_{jit},\ R_{it},\ t\ ;\ \delta) \quad = \quad e^{v_{it}-u_{it}} \tag{1}$$

in which inputs $x_{kit} \in_{+}^{k}$, $k = 1 \ldots K$, and outputs $y_{jit} \in_{+}^{M}, j = 1 \ldots M$ are in scalar form; $t = 1 \ldots S$ is a time trend proxying for technical change; $i = 1 \ldots N$ defines each observation; R_{it} are Brazil's road densities; δ is an estimable parameter; $u_{it} \sim N^{+}(\mu,\ \sigma^2)$ is a nonnegative, half-normally distributed error representing an observation's departure from its technical frontier; and v_{it} is an independently and identically distributed (iid) random noise with mean zero and variance σ_v^2 (AIGNER et al., 1977). Error terms v_{it} and u_{it} are assumed distributed independently of one another: $\sigma_{vu} = 0$.

Re-specifying the left hand side of (1) in exponential form

$\left[D_I(\cdot) \;=\; e^{g(\ln x_{kit},\, \ln y_{jit},\, \ln R_{it},\, t;\, \delta)}\text{; where } g \text{ is a function} \right]$ gives an expression of a given observation's stochastic distance to the technically efficient frontier. Converting that expression into the distance frontier employed in the present analysis requires imposing linear homogeneity in inputs (SHEPHARD, 1970). This may be done by allowing $x^*_{kit} = x_{kit} / x_{lit} \neq +\infty$, in which the l^{th} input is employed as numeraire (LOVELL et al., 1994). Rearranging terms, taking logs, and modeling inefficiency error u_{it} after Battese and Coelli's (1992) time-effect parameterization -- $u_{it} = u_i \exp[-\eta(t - S_i)] = u_i\eta_{it}$; where η is an iid random variable to be estimated -- brings

$$-\ln x_{lit} = g(\ln x^*_{kit},\; \ln y_{jit},\; \ln R_{it},\, t\,;\; \delta) - v_{it} + u_i\eta_{it} \tag{2}$$

3.3 Econometric Approach

The decennially-collected Brazilian agricultural census data brings great advantages for investigating TFP but also limitations. The most prominent limitation is the relatively few time-series sample points available for measuring technical change. This paucity of time-series data constrains the ability to employ flexible functional forms such as the translog. And because of their collinearity with the time trend, it limits possibilities for estimating policy influences on an agricultural technology.[2] In face of these limitations, the log of Brazil's agricultural input distance frontier is expressed here in the somewhat less flexible generalized Cobb-Douglas form

$$g(\ln x^*_{kit},\; \ln y_{jit},\; \ln R_{it},\, t\,;\; \delta) = \delta_0 + \sum_{k=1}^{K-1} \delta_k \ln x^*_{kit} + \sum_{j=1}^{M} \delta_j \ln y_{jit} + \delta_R \ln R_{it} + \delta_t t \tag{3}$$

Where subscript k indexes family labor, hired labor, capital, and materials, respectively; j indexes crops or livestock; i indexes 558

Brazilian microregions; and t is the time trend spanning three consecutive censuses (1985, 1995/6, and 2006). The l^{th} input, used as numeraire to impose linear homogeneity, is land, allowing for a per-hectare interpretation of each normalized input.

One of the many advantages of Brazil's agricultural census data is its rich cross-section, information exploited here to allocate each micro-region to its respective biome. Using Geographic Information Systems (GIS), the centroid of each micro-region is located in relation to Brazil's GIS-mapped biomes (Fig. 1). Biomes, however, are not defined by political boundaries. When a micro-region straddles several biomes, a biome's input and output allocations are here computed on the basis of the biome in which the majority of the micro-region's municipalities or counties reside. Five microregions, constituting 0.9% of the sample total, are equally split between biomes. These were allocated by determining in which biome the micro-region had the greatest land area.

Because the focus of the present analysis is on biome-specific TFP growth rates, it is important to control for state-wise, time-invariant, unobserved heterogeneity. Stochastic frontier methods often incorporate fixed effects through inefficiency error u_{it}. That approach, as noted by Greene (2005), may confound state-wise and time-wise inefficiency with all other unobserved heterogeneity across states. Alternatively, dummy variable P_h, $h = 1,...,H$ may account for state-wise, time-invariant heterogeneity, leaving error u_{it} to account for any agricultural inefficiency.[3] Incorporating dummy variable P_h into equation (3), rewriting its right-hand side as $g(P_h,\ \ln x^*_{kit},\ \ln y_{jit},\ \ln R_{it}, t\ ;\ \delta)$, and substituting that into equation (2) gives

$$-\ln x_{lit} \;=\; g(P_h,\ \ln x^*_{kit},\ \ln y_{jit},\ \ln R_{it}, t\ ;\ \delta) \;-\; \nu_{it} \;+\; u_i\eta_{it}. \quad (4)$$

Technical change in (4) is measured by the model's time trend, allowing one to statistically distinguish among the technical change rates in the various crop and livestock subsectors of the Brazilian agricultural economy. Technical change statistics are computed by successively differentiating parameter estimates, presented in Appendix Table B1, with respect to each output group and the time trend, then applying the implicit function theorem. Technical change is interpreted here as the factor productivity of the most efficient producers because it is those observations that account for any expansion of the production possibilities frontier.

After obtaining the two subsectors' (crops and livestock) technical change estimates, we weight them by their respective mean revenue shares to obtain one aggregate (all-agriculture) technical change statistic. After estimating equation (4), each micro-region's technical efficiency level in each census year is obtained from

$$E(TE_{it}) = E\left[e^{-u_i \eta_{it}}\right]. \tag{5}$$

Each biome's TFP growth rate is then computed as the sum of the aggregate technical change rate in equation (4) and the mean technical efficiency change rate computed from equation (5).

4. Data

Three Brazilian agricultural censuses (1985, 1995/6, 2006) are chosen for the present analysis, providing panel data for 558 microregions and covering 20 outputs and 11 inputs. The farm-level survey data are employed at two aggregation levels: micro-region and state (Table 1). Descriptive statistics for both output and input data are provided in Table 2.

4.1 Production Data

The 20 commodities included in this analysis are from the micro-region data, recorded in metric tons, and aggregated into two revenue-share-weighted quantity indexes: crops and livestock. Crops accounted for 72% of total revenue in 1985, livestock making up the other 28%. By 2006, the livestock sub-sector had gained 6 percentage points, shifting those respective shares to 66% and 34%.

The majority of recorded production inputs are available in the censuses at the micro-region level. They are hectares of agricultural land and fertilizer, feed, seed, pesticides, livestock vaccines, and electricity expenditures. Although some labor, livestock, and farm machinery data are available at the micro-region level, the remaining are state aggregations. The infrastructure data, recorded in the annual statistical yearbooks, are available at the state level. All data not available at the micro-region level are imputed to the micro-region and described in Appendix A. Each of Brazil's 27 states, themselves comprised of the 558 microregions, is shown in Fig. 1. Because the Brazilian currency changed five times between 1984 and 1994, 1985 output and input prices are converted to Reais.[4] All 1985 and 1995/6 prices are then normalized to a 2006 basis using the Internal Availability General Price Index (IGP-DI), which captures wholesale, consumer, and construction price changes (IBRE, 2010).

4.2 Evaluating the Production Data by Biome

Each variable's description, unit of measurement, number of microregions, and mean values by biome, are provided in Table 2. Unsurprisingly, mean crop and livestock production in the Cerrado exceeds that in the Eastern biomes by a factor of 1.6 and 1.4, respectively, indicating the Cerrado's larger scale of operations. Indeed, not only does an average farm (representative of that average micro-region) produce more than its counterparts in the East, it also employs substantially more resources.

For instance, an average farm in the Cerrado spends 2.6 times as much on material applications (fertilizer, pesticides, animal vaccines, seed, feed, and electricity) and twice as much on capital services (machinery and livestock) as a farm in the Eastern biome. Moreover, the farm in the Cerrado employs 2.8 times as much quality-adjusted land. These descriptive statistics underline the disproportionately resource-intensive nature of producing agricultural commodities in the Brazilian savannah.

4.3 Road Densities

Lengths of road, in kilometers, are available in various Brazilian statistical yearbooks at the state-level and account for roads under municipal, state, and federal jurisdictions. State-level paved road densities employed in this analysis are then measured as the sum of the length of asphalted road, divided by the state's geographic area. Brazilian statistical yearbooks show that 1.58 million kilometers of road were built in 2006, 11.4% of them paved. That was an improvement over the 1.38 million kilometers of road in 1985, of which only 5% were paved (AEB, 2008; AEB, 1986). Paved roads are particularly important to Brazilian producers because the cost of traversing paved roads is one-third that of unpaved roads (VERA-DIAZ et al., 2009).

5. Results

Models (4)-(5) were estimated by STATA 12 with full information maximum likelihood. Coefficient estimates of distance frontier (4) are provided in Appendix Table B1 for each biome grouping.[5] Technical change estimates are provided in Table 3, and mean technical efficiency changes and total factor productivity growth rates in Table 4.[6]

The highest pair-wise correlation, across all biome applications of equation (4), is the 0.81 between hired and family labor in the Eastern biome. But because that same pair-wise correlation is 0.65 in the Cerrado biome, both labor variables are retained in every biome-specific regression to maintain model consistency.[7] Such consistency is especially important for generating a national biome-revenue-share-weighted average TFP growth rate, a computation allowing comparability of the present study's results with other Brazilian agricultural TFP evaluations. Apart from the two labor variables, no pair-wise correlation exceeds 0.59.

Underlying the productivity focus in the present analysis is the objective of generating new information to help shape the dialogue over Brazilian agriculture's long-term prospects and competitive potential. Yet various factors, in particular the growth of the urban, industrial, and – most recently – rural tourism sub-sectors have induced some Brazilian farms to abandon commercial agriculture. It is thus logical to examine only the observations which appear to represent competitive firms. On the basis of a comparison of 2006 with 1985 production levels, thirteen observations are regarded as corresponding to an abandonment of competitive agriculture and thus omitted. Six others were omitted due to incomplete data.

5.1 Technical Change

Brazil's most efficient farms, as noted by Table 3, have extended their production possibilities at rapid rates; no single biome's informal (time-related) technical change rate, for either crops or livestock, has been below 3.9% per annum. The best-practice factor productivity growth rates in the Eastern and Cerrado biomes are consistent with results from Rada and Buccola (2012), who found livestock's technical progress to have outstripped that of crops. By far the most outstanding statistic in Table 3, though, is the Eastern biome's annual 12% livestock informal technical change rate. Such improvement in the factor productivity of the livestock sub-sector's most efficient producers helps explain Brazil's rapid rise as a global meat trade competitor. Using the Food and Agriculture Organization's FAOSTAT database, we find Brazil's volume share of global meat trade rose 17.4% each year between 1997 and 2007, topping out at 18.1% in 2007 and matching the U.S.'s 17.6% share in 2008 (FAO, 2011).

Paved roads have been particularly instrumental in extending farm production technologies in the Cerrado: a 1% increase in its density boosted crop production by 0.86% and livestock production by 0.91%. Road development, however, appears not to have performed as well in the Eastern and Western biomes. The paved-road variable in the Eastern biome is not statistically significant; in the Western biome, its coefficient is negative and statistically significant at the 10% level. A test of whether the Western biome's paved-road coefficient equals zero is rejected at the 5% but not the 10% level. The negative sign on the Western biome's statistically significant road coefficient, and its statistical insignificance in the Eastern biome, are robust to a variety of model permutations.[8]

Upon accounting for road contributions in Table 3, each biome's annualized total technical change rate is weighted by its respective mean 1985 – 2006 output revenue share. Surprisingly, the Cerrado biome has enjoyed, of the three biome groupings, the lowest aggregate technical change rate (4.6%), another result robust to model permutations. Given the Amazônia biome's very low base (its 6% mean revenue share), high rates of technical progress among the most efficient producers are not unexpected, as marginal improvements to a low base often produce large percentage changes. The Eastern biome's very rapid aggregated technical progress (7.3% per annum) is, however, exceptional. That biome accounted for a mean 67% of total revenues during the three census periods; yet its most efficient producers also achieved the most rapid efficiency improvements, largely on the progress made in its livestock sub-sector. Indeed, the Eastern biome's share of total livestock revenues averaged 63.8% between 1985 and 2006, further emphasizing the biome's outstanding livestock technical progress.

5.2 Technical Efficiency Change and TFP Growth

The technical efficiency changes provided in column 1 of Table 4 show that in each biome, average producers were unable to match the performance of the most efficient farms. For instance, while the most efficient farms in the Cerrado progressed at an impressive 4.6% annualized pace, average farm productivity rose by only 0.4% per annum, the gap between frontier and average farm expanding 4.2% each year. Surprisingly, the Eastern biome not only achieved Brazil's most rapid technical progress but, at 4.2% per annum, the fastest average-farm total factor productivity growth. The Eastern biome's average-farm TFP growth rate clearly lifts the entire nation's TFP growth (Table 4).

In the Western biome, the rate of technical efficiency *loss* has exceeded the rate of technical progress (outward shift in the production possibility frontier), so that total annual factor productivity growth has been a negative 0.87%. This suggests that while efficiency on some farms (possibly those bordering the Cerrado) improved rapidly, input growth has exceeded production gains and is likely a result of resource degradation. Yet the index-number-generated TFP growth rates of Gasques et al. (2010) in the 1985 – 2006 period by Brazilian state and of Avila et al. (2013) in the 1975 – 2006 period by biome do not suggest negative agricultural TFP growth. Methodological differences may partially explain this difference. But the likely more important factors include the greater number of outputs (367) that Gasques et al. account for, the different period evaluated by Avila et al., and the different approach used to measure inputs by each study. For instance, while Gasques et al. account for a greater number of material inputs and assume that all land is of equal quality, the present analysis accounts for more capital and labor inputs and adjusts for each land type's distinct productive capacity. In spite of these differences, weighting each biome's TFP growth rate (column 2 of table 4) by its respective mean revenue share over the 1985 – 2006 period generates a national biome-aggregated TFP growth rate of 2.89% per annum. This estimate is very close to rate in the only other studies employing 1985 - 2006 Brazilian census data: Gasques et al.'s index number estimate of 2.87%, and Rada and Buccola's (2012) input distance frontier estimate of 2.62%.[9]

6. Discussion

In isolating and evaluating the productive performance of the Brazilian Cerrado, new information is presented that may help us understand the resource cost of producing in a savannah and how the targeting of infrastructural investments might be improved.

6.1 Road Density's Uneven Impact

Paved-road density's impact varied widely by biome, but in the Cerrado was significant. It is thus reasonable to ask what information might best assist policy makers in targeting infrastructural investments to boost farm productivity. The present results suggest road systems' productivity performance (Table 3) may depend on the level of infrastructural development, which in Brazil is quite uneven. The failure of farms in such highly developed regions as the Brazilian South and Southeast to benefit from additional road density is likely because roads there already are heavily paved. Eighty-three percent of the South and Southeast microregions are in the Mata Atlântica biome and account for an average 65% of all paved roads in the 1985 – 2006 period. In contrast, the failure of farms in such infrastructure-poor regions as the Western biome to benefit from new road construction might well be because farm production there is inadequately commercial to exploit it. Brazil's northern states dominate the Amazônia biome and account for only a 7.7% mean share of 1985 – 2006 paved roads. Indeed, a negative coefficient may represent the substantial set-up cost of developing a commercial farm in that region.

The Cerrado, however, represents a region of what may be termed moderate infrastructural development. For every square kilometer of the Cerrado, there is 0.03 kilometers of paved roads, namely less than 60%

of the paved road density in the Eastern biomes (Table 2). Productivity in such an area might receive an especially strong lift from paved-road construction because commercial-farm and infrastructure capital are largely in balance there, enabling greater exploitation of density improvements. Thus, our findings appear to suggest that road paving has the highest productivity payoff when targeted toward a region's most efficient producers and toward areas in which infrastructure capital is a primary constraint.

6.2 Assessing the Productive Performance of the Cerrado

Producers at the Cerrado's technical frontier, that is those who managed their resources most efficiently, have enjoyed an average TFP growth rate of 4.6%. But the great majority of enterprises were unable to match that efficiency, so that overall average TFP growth rate was only 0.4%. This 4.2% TFP gap suggests considerable room for efficiency improvement and thus for production levels well above those in 2006.

Central to our objectives is to estimate the resource cost of producing in the Brazilian Cerrado. To answer that question we compute, between 1985 and 2006 and for all 318 microregions, the Cerrado's average revenue-share-weighted production growth. Between those years, the Cerrado's logged mean growth rose 192%, from 146,088 to 995,563 tons. But the Cerrado's logged TFP growth implies the average farm produced only 8.3% more in 2006 than in 1985 without applying more inputs. Because the log of TFP growth is the difference between logged output growth and logged input growth, these estimates suggest that only 8.3% of the 192% production rise can be accounted for by improved efficiency or technology. Stated differently, given that TFP growth accounted for 16% of production growth, the use of additional inputs must have accounted for the remaining 176%, confirming the high resource cost of Cerrado farming. Production growth on the average Cerrado farm thus is based predominantly on bringing more labor, land, materials, and capital into production rather than on improving the efficiency of existing resources.

Further evaluations of the substantial gains in Brazil's agricultural development might well focus on the impact of scale economies to the Cerrado biome's productivity growth. The sources of any such scale economies would be captured in our TFP measures presented above. But given the large TFP gap between the Cerrado's average and most efficient producers, it would be interesting to ask whether these most-efficient farms are large commercial ones or smallholders. Helfand and Levine (2004) find a nonlinear relationship between farm size and technical efficiency, the efficiency first declining and then rising with farm size. But they do so in a two-stage approach rather than by decomposing TFP growth into its technical progress, efficiency change, and scale economy components, and they focus on the entire Center-West region rather than Cerrado biome. Isolating the contribution of scale economies to the Cerrado's TFP growth would improve our understanding of the forces behind the Cerrado's 'agricultural miracle' and more generally help target the policies designed to promote savannah agricultural growth.

7. Conclusion

This paper finds that agricultural production in the Brazilian savannah has been highly resource-intensive. While the Cerrado's most efficient farms have accelerated production in part through substantial efficiency improvements, the majority of farms have boosted production largely through greater resource use. This suggests that any agricultural transformation of native savannah, in the Brazilian Cerrado, Guinea Savannah, or elsewhere, will have high resource cost. Paved road investments have played a significant role in boosting the productivity growth of the Cerrado's most efficient producers. Because road-paving impacts have varied widely across biomes, such infrastructural investments appear to bring a particularly high return when targeted toward areas in which paved roads are a major limitation to agricultural growth.

Brazil could substantially improve its global competitive position in the supply of important farm commodities by improving average efficiency in the Cerrado itself, such as by pushing average-performing farmers toward the technologies and management practices of those on the technical frontier. That would provide a significant contribution toward the 60% global food supply rise that some spokesmen have called for by mid-century. Optimal growth policy in the world's other savannah regions such as the Guinea Savannah is less clear. Whether, as in the Cerrado, a large-scale commercial agricultural approach is taken, or as recommended by Morris et al (2012) smallholder-led commercialization instead is adopted, success will depend on the real prices of the substantial material input quantities shown in the Cerrado to be required for maintaining adequate plant growth under savannah conditions. Costs of material inputs like fertilizers, pesticides, feed, seed, and power appears indeed to be a great constraint to raising farm production when expanding onto new arable lands of low nutrient composition.

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

Figura 1. Brazilian States and Biomes

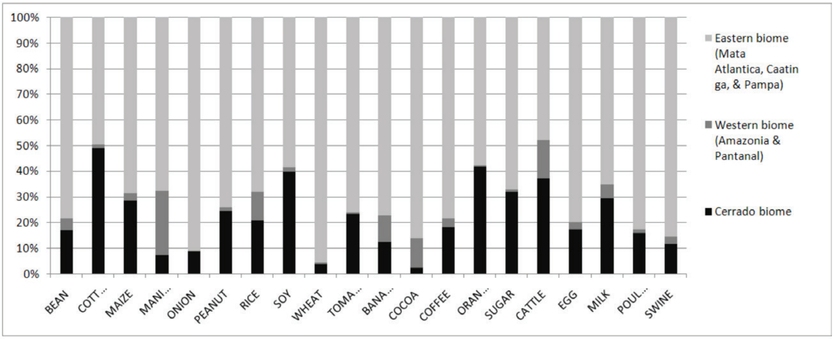
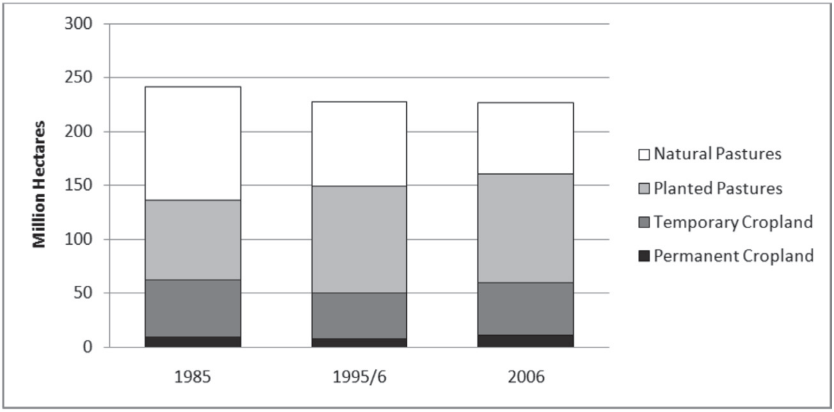


Figura 2. Commodity Production Shares by Biome Grouping, Averaged Across Census Years, 1985 – 2006



Source: IBGE, 2010.

Figura 3. Land Groups by Census Year, 1985 – 2006

Table 1. Data Sources

Series	Level of aggregation	Source
Commodity production	Microregion	IBGE
Farm level commodity prices	Microregion	IBGE
Agricultural land use	Microregion	IBGE
Persons employed primarily in agriculture	State & Microregion	Avila and Evenson (1995) & IBGE
Material expenditures	Microregion	IBGE
Tractors in use	Microregion	IBGE
Tractor service prices	State	Barros (1999)
Livestock capital	Microregion	IBGE
Farm animal prices	State & microregion	IBGE
Road density (km/area)	State	Annual Statistical Yearbooks[a]

Note: IBGE is the Brazilian Institute of Geography and Statistics.

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

Table 2. Descriptive Statistics, 1985 - 2006

Biome:			Western		Cerrado		Eastern	
Variable	Description	Unit of obs.	Number of microregions (obs.)	Mean values	Number of microregions (obs.)	Mean values	Number of microregions (obs.)	Mean values
Crops	Beans, cotton, maize, manioc, onion, groundnuts, rice, soybeans, wheat, tomato, bananas, cocoa, coffee, oranges, and sugarcane	Metric tons	219	9,744	318	98,598	1,080	59,418
Livestock	Cattle meat, eggs, cow milk, poultry meat, and pig meat	Metric tons	219	5,579	318	15,664	1,080	10,821
Family labor	Male-labor equivalents	Count	219	28,694	318	21,613	1,080	17,328
Hired labor	Male-labor equivalents	Count	219	3,946	318	9,188	1,080	5,112
Land	Temporary-cropland-equivalents	Hectares	219	96,956	318	199,614	1,080	71,914
Capital	Machinery and livestock capital service expenditures	Thousands of constant 2006 Reais	219	37,387	318	91,066	1,080	44,948
Materials	Fertilizer, seed, pesticide, animal vaccine, feed, and electricity expenditures	Thousands of constant 2006 Reais	219	24,873	318	135,842	1,080	51,239
Paved roads	Kilometers of paved roads per square kilometers of area	Density	219	0.005	318	0.033	1,080	0.056

Note: Mean estimates are for observations with positive values only and are unweighted.

Table 3. Average Annual Technical Change Contributions, 1985-2006

Biome	*Output*	*Informal Technical Change Rates(TCR)*	*Output Elasticity of Roads*	*Time Rate of Change in Roads*[c]	*Roads Impact*	*Total TCR*	*Output's Revenue Share Weights*	*Biome's Aggregated TCR*
Western[a]	Crops	7.03%	-0.73%	0.045	-0.03%	7.03%	48%	5.39%
	Livestock	3.93%	-0.41%		-0.02%	3.93%	52%	
Cerrado	Crops	4.47%	0.86%	0.033	0.03%	4.50%	63%	4.58%
	Livestock	4.70%	0.91%		0.03%	4.73%	37%	
Eastern[b]	Crops	4.59%	0.00%	0.017	0.00%	4.59%	65%	7.34%
	Livestock	12.55%	0.00%		0.00%	12.55%	35%	

The Western biome grouping consists of the Amazônia and Pantanal biomes.

[b] The Eastern biome grouping consists of the Mata Atlântica, Caatinga, and Pampa biomes.

[c] Time rates of change are rounded to the third decimal point.

Table 4. Average Technical Efficiency (T.E.) Changes and TFP Growth, 1985-2006

Biome	Average Annual T.E. Change, 1985 – 2006	Average Annual TFP Growth, 1985 – 2006
Western[a]	-6.27%	-0.88%
Cerrado	-4.17%	0.40%
Eastern[b]	-3.10%	4.24%

[a] The Western biome grouping consists of the Amazônia and Pantanal biomes.

[b] The Eastern biome grouping consists of the Mata Atlântica, Caatinga, and Pampa biomes.

Appendix A. Data

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

Labor

Labor's contribution to production is represented by two male-equivalent labor quantity indexes: hired and family labor. 1985 and 1995/6 state-level labor counts are obtained from Avila and Evenson (1995) and 2006 micro-region-level labor counts from the Brazilian Institute of Geography and Statistics (IBGE, 2010). Female labor is quality-adjusted to male-labor equivalents, using the mean ratio of 1998 – 2002 female to male agricultural wage rates specific to Brazil (ILO, 2010). Over that time period, female agricultural labor wages were on average 92% of male wages.

The 1985 and 1995/6 state labor counts require interpolation to the micro-region. Those labor counts are available by type (i.e., family, permanent-hired, and temporary-hired) and agricultural sub-sector (crop, livestock, and forestry). Following Avila and Evenson (1995), each labor type engaged in the livestock sub-sector is weighted by the micro-region's state share of livestock sold. Labor engaged in crop agriculture is interpolated to the micro-region by weighting each labor type by the micro-region's share of total cropland. Every state's forestry labor is distributed equally to each micro-region in that state.

In constructing the male-equivalent hired labor index, permanent and temporary labor are summed and multiplied by each state's agricultural-labor gender share, then re-aggregated using the ILO wage data. A similar approach is taken for family labor to construct its male-equivalent labor index. Because the 2006 census labor data are available by gender and type at the micro-region level, no interpolation is required to obtain the family and hired-labor male-equivalent quantity indexes.

Land

Hectares of land are available at the micro-regional level in each census, quality differentiated into four groups: permanent cropland, temporary cropland, natural pasture, and planted pasture. The planting of perennials distinguishes permanent from temporary cropland, which is itself planted to annuals, forages, and flowers. Because reliable land rental rates are unavailable, Fuglie's (2010) method of estimating relative land weights for each land group and census period is followed to generate a temporary-cropland-equivalent land series. Those weights are available in Rada and Buccola (2012). Quality-adjusting land is important when measuring productivity growth because bias might arise in the land series if land changes occur unevenly among groups (FUGLIE 2008), as was the case in Brazil. The land weights indicate temporary cropland is assumed the most productive in 1985 and 2006, permanent cropland taking that mantle in 1995/6.

Capital

Unlike the land and labor quantity indexes, the capital index is expressed as expenditures on farm machinery and livestock services. The farm machinery data is limited to tractors, 1985 census data shortage restricting the measure from a broader range of mechanical implements. Barros (1999) provides state-level 1985 and 1995/6 tractor service prices. These prices are estimated by using new and used 1997 – 98 prices of two Massey Fergusson tractor sizes, amortized over 21 years at a 7% depreciation rate, converted to *Reais*, and deflated by the FGV's IGP-DI to a 2006 basis. The 1985 and 1995/6 capital service expenditures are thus the estimated service prices multiplied by 1985 and 1995/6 census-provided counts of tractors-in-use. Year 2006 tractor service prices are obtained by multiplying the 1995/6 annual service price by the IGP-DI conversion to 2006, then multiplying that price against the 2006 census' tractors-in-use.

State-level data in the 1985 and 1995/6, and micro-region data in the 2006 census, of on-farm stocks of bulls and steers, bovines, horses, asses, mules, pigs, goats, chickens, roosters, and hens are used to construct this study's livestock capital. Each animal is aggregated to bovine equivalents using Hayami and Ruttan's (1985, p. 450) cattle-normalized weights. State bovine-equivalent animal stocks are interpolated to every micro-region by multiplying the state stock by each micro-region's state share of livestock sold. Bovine sale prices, available by state in 1985 and by micro-region in 1995/6 and 2006, are amortized over ten years at a 10% discount rate to obtain the bovine-equivalent capital service price. The bovine-equivalent animal stocks are then multiplied by the service price, obtaining the livestock capital service expenditures.

Materials

Much like the capital expenditure index, materials are also constructed into an expenditure index. Fertilizer, seed, pesticide, animal vaccine, feed, and electricity expenditures constitute that material service expenditure index. These farm expenditures are available from each census at the micro-region level. Year 1985 material expenditures are converted to Reais and then deflated to a 2006 basis using the IGP-DI price index.

Appendix Table B1. Biome-Specific Distance Frontier Parameter Estimates

Dep. Var.: -Land	Coefficients		
	Western Biome	Cerrado Biome	Eastern Biome
t	0.083***	0.059***	0.058***
Livestock	-0.212***	-0.125***	-0.046***
Crops	-0.119***	-0.131***	-0.127***
Family Labor	0.188***	-0.032	0.023
Hired Labor	0.060	0.086***	0.034**
Capital	0.285***	0.538***	0.320***
Materials	0.127***	0.059***	0.027***
Roads	-0.087*	0.113***	0.027
Rondônia	-0.392	--	--
Acre	-0.409	--	--
Amazonas	-0.343	--	--
Roraima	-0.688*	--	--
Para	-0.398	--	--
Amapa	-0.524	--	--
Tocantins	-0.435	0.703***	--
Maranhão	-0.224	0.688***	--
Piauí	--	0.633***	0.161
Ceará	--	--	0.235
Rio Grande do Norte	--	--	0.185

Appendix Table B1. Biome-Specific Distance Frontier Parameter Estimates, continued

Dep. Var.: -Land	Coefficients		
	Western Biome	Cerrado Biome	Eastern Biome
Paraiba	--	--	0.189
Pernambuco	--	--	0.215
Alagoas	--	--	0.166
Sergípe	--	--	0.134
Bahia	--	0.508***	0.195
Minas Gerais	--	0.585***	0.184
Espírito Santo	--	--	0.140
Rio de Janeiro	--	--	0.228
São Paulo	--	0.342***	0.198
Parana	--	0.361**	0.172
Santa Catarina	--	--	0.137
Rio Grande do Sul	--	--	0.161
Mato Grosso do Sul	-0.200	0.618***	0.258
Mato Grosso	-0.372	0.737***	--
Goiás	--	0.573***	--
Federal District	--	0.333**	--
/mu	1.591***	1.06***	0.814***
/eta	-0.091***	-0.087***	-0.078***
/lnsigma2	-1.349***	-1.903***	-2.355***

Appendix Table B1. Biome-Specific Distance Frontier Parameter Estimates, continued

Dep. Var.: -Land	*Coefficients*		
	Western Biome	Cerrado Biome	Eastern Biome
/ilgtgamma	1.756***	2.105***	1.588***
sigma2	0.259	0.149	0.095
gamma	0.852	0.891	0.830
sigma_u2	0.221	0.132	0.079
sigma_v2	0.038	0.016	0.016
Number of Observations	219	318	1080
Model's Log Likelihood	-27.55	80.05	349.89

Note: All production output and input variables except *t* are logged.

Endnotes

1 All material expenditures are normalized to 2006 Reais.

2 Attempts to include various policy variables, such as stocks of Embrapa's agricultural research expenditures, into the technology function were met with heavy collinearity with the time trend.

3 Such an approach is recommended by Greene (2005) for efficiency measurement provided dummy variable P_h accounts for unobserved heterogeneity that is not efficiency related.

4 The reader is referred to Rada and Buccola (2012) for a review of the currency changes in Brazil.

5 In updating the analysis, a small computational error had been found in the livestock capital measure. The estimates provided here reflect a correction of that error.

6 Because the Brazilian census data are decennial, linear annual growth across a given decade is assumed to allow for result comparability with other analyses. For instance, the Cerrado's annual 4.33% rate of technical change in table 4 reflects a 43.32% per-decade rate of change over the 1985 – 2006 period.

7 Omitting hired labor from each model does not alter the nationally biome-aggregated total factor productivity growth rate by more than 0.05%

8 An alternative road density specification was tested. That variable interpolated state road lengths in each census period to the micro-region level using fixed GIS weights. The weights were estimates of 1999 road lengths per micro-region (IBGE, 1999). Upon interpolating each state's road lengths to the micro-region, the values were divided by each micro-region's GIS-estimate of land area, computed by the Economic Research Service (USDA), generating each micro-region's road density in each census year. This alternative specification was highly statistically insignificant in each biome model and was outperformed by the state-level road specification presently included in the analysis.

9 Gasques et al. (2010) report that Brazil's national productivity growth rate between 1985 and 2006 has been an average annual 2.28%. If, however, we examine state productivity growth rate averages, we find an unweighted average annual rate of 2.87% and a mean revenue-share weighted average annual rate of 2.33%. Because the methodology presented here estimates the unweighted average change across microregions, we highlight Gasques et al's unweighted estimates.