WORKING PAPER

TECHNOLOGICAL CHANGE AND DEFORESTATION:
EVIDENCE FROM THE BRAZILIAN SOYBEAN REVOLUTION

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AUGUST 2015

THEME
AGRICULTURE

KEYWORDS
TECHNOLOGICAL CHANGE, AGRICULTURE, LAND USE, DEFORESTATION

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Technological Change and Deforestation: Evidence from the Brazilian Soybean Revolution*

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March 2015

Abstract

This paper studies the impact of technological change in agriculture on land use in Central Brazil from 1960 to 1985. It explores technological innovations that adapted soybeans to the region to estimate the effect of these innovations on land use. Following the technological innovations, municipalities more suitable for soybean cultivation experienced increases in cropland and decreases in native pastures. The rise in cropland was smaller than the decline in native pastures and, as a consequence, deforestation increased less in municipalities more suitable for soybean cultivation. Increases in fertilizer adoption and tractor use accompanied the changes in land use, suggesting that technological innovations induced substitution from investments in forest clearing for investments in agricultural intensification. These results are consistent with a model in which farmers are capital constrained and in which crop cultivation is more capital-intensive than cattle grazing.

JEL: *N56, O13, Q16, Q24.*
Keywords: *Technical Change, Agriculture, Land Use, Deforestation*

*We are grateful to Rodrigo Adao, Avery Cohn, Claudio Ferraz, Gustavo Gonzaga, Bernardo Mueller, Marcelo Paiva Abreu, Heitor Pellegrina, Leonardo Rezende, Rodrigo Soares, Judson Valentim, and seminar participants at Brown, CEDEPLAR/UFMG, Harvard DRCLAS, and PUC-Rio for valuable comments and suggestions. We thank Dimitri Szerman for the assistance with the agricultural census data. We acknowledge financial support from CNPq and the Climate Policy Initiative.

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1 Introduction

"(...) nobody thought these soils were ever going to be productive"
Norman Borlaug, The New York Times, October 2007

Deforestation is an important determinant of global climate change and accounts for about one-quarter of global greenhouse emissions (IPCC, 2014). This phenomenon is concentrated in tropical areas and reducing its prevalence is essential to mitigate global climate change (Stern, 2007; Kindermann et al., 2008). There is concern, however, that policies that promote agricultural development are inimical to forest conservation (CPI, 2013).

Investments in agricultural research are considered one of the most relevant policies to promote agricultural development (WDR, 2008). The existing literature identifies substantial economic benefits from these investments (Evenson, 2001). Nevertheless, whether these investments will increase or decrease deforestation is an important and controversial question for development and environmental policies. Its answer will change if technical change in agriculture induces farmers to expand in the extensive margin or not.

The influential idea of the Jevons Paradox suggests that technical change in agriculture induces agriculture to expand in the extensive margin and increases deforestation. This result is a consequence of technological improvements increasing the marginal product of land and inducing farmers to increase land use. Nevertheless, the arrival of modern agricultural technologies often induce farmers to increase input use and adopt different agricultural practices. Farmers facing labor or capital constraints do not have enough resources to make these investments and clear forests. These farmers must choose between investing in inputs and modern agricultural practices and forest clearing. To the extent that it induces investments in inputs and agricultural practices, technical change in agriculture can reduce forest clearing. Therefore, the theoretical relationship between technical change and deforestation is ambiguous, being essential to provide empirical evidence on this matter.[1]

Long run adjustments to technical change episodes can be useful to provide evidence on this issue. In this paper, we use the historical experience from Central Brazil to examine the effects of technical change in agriculture on land use. We explore exogenous variation coming from the technological innovations that adapted soybeans to the region's agro-climatic characteristics to investigate the effect of technical change in agriculture on

[1] Investments in agricultural research increase agricultural production that can influence agricultural prices. An important literature argues that this macroeconomic mechanism can affect the relationship between technical change and land use (Borlaug, 2007; Ewers et al., 2009; Rudel et al., 2009; Hertel et al., 2014). We abstract from this effect throughout the paper.

land use. The soils in Central Brazil are naturally acid and poor in nutrients and were considered inadequate for commercial agriculture until 1970. Biological innovations implemented throughout the 1970s made commercial soybean cultivation possible and revolutionized agriculture in the region (Spehar, 1994; de Almeida et al., 1999; Salim, 1986).

These innovations allowed farmers to move from extensive cattle ranching using almost no modern inputs to intensive soybean cultivation using modern inputs and machines (Klink and Moreira, 2002; Monteiro et al., 2012). Conservation policies did not influence the changes in land use as these policies were nonexistent in the period. Therefore, we investigate the effects of technical change in agriculture on land use in a context in which environmental regulation did not limit land use.[2]

To guide the empirical investigation, we propose a simple model in which farmers choose to use land for crop cultivation or cattle grazing. We assume that crop cultivation is more capital-intensive than cattle grazing and that farmers can be capital constrained. Historical accounts indicating that crop cultivation in Central Brazil required substantial investments in fertilizers and tractors to be feasible motivate these assumptions.

We model technical change as an increase in the relative return to crop cultivation compared to cattle grazing. Technical change results in an unambiguous increase in cropland area. However, its effect on deforestation is ambiguous. Cropland expands over native forests and deforestation increases in the absence of capital constraints, as suggested by the Jevons Paradox. However, cropland expands over pastures when there are capital constraints. In this case, the increase in cropland is smaller than the decrease in pastures and deforestation decreases.

The model is used to interpret the effects of the technological innovations that adapted soybeans to Central Brazil on land use. To estimate the impact of these innovations, we combine the timing of the innovations with variation in agronomic potential for soybean cultivation using modern technologies across municipalities in the region. The identification strategy resembles a differences-in-differences and estimates relative changes in land use in municipalities more suitable for soybean cultivation compared to municipalities less suitable for soybean cultivation. Its estimates capture the causal impact from the technological innovations on land use under the usual differences-in-differences assumption that outcomes would have changed similarly across municipalities in the absence of

[2]It is important to observe that the technological innovations studied in this paper did not influence agricultural prices. Crop and meat production in the region was too limited to influence prices either at the national or international level. Thus, the influence from these innovations on land use are related to microeconomic and not to macroeconomic mechanisms.

the innovations. This estimation strategy allow us to separate the effects of the technological innovations from the expansion in the agricultural frontier that was happening in the period in Central Brazil.

We use the GAEZ global database of theoretical soil productivities to construct a municipality measure of the agronomic potential for soybean cultivation using modern technologies in Central Brazil.[3] We then estimate relative changes in land use in municipalities more suitable for soybean cultivation when compared to municipalities less suitable for soybean cultivation using data from the Brazilian Agricultural Census from the period 1960 to 1985. Our data includes five waves of the Brazilian Agricultural Census (1960, 1970, 1975, 1980, and 1985).

Since the technological innovations occurred throughout the 1970s, the data includes two periods before the treatment, two periods during the treatment, and one period after the treatment. The baseline specifications include geographic and baseline municipality characteristics as controls to mitigate the concern that differential trends in the outcomes drive the results. We provide evidence that pre-treatment trends were similar across municipalities in the region, lending support to the empirical design.

The empirical estimates indicate that technological innovations that adapted soybeans to Central Brazil created substantial economic and environmental benefits. Total farmland increased fast in the region during the sample period which created substantial environmental pressures. Nevertheless, our results suggest that the technological innovations attenuated these pressures. We find that the technological innovations are not associated with increases in total farmland. These innovations are associated with changes in land use from pastures to cropland. Native pastures declined faster in municipalities more suitable for soybean cultivation using modern technologies while cropland increased faster in these municipalities. Cropland expansion was smaller than native pastures decline as predicted by the model when farmers are capital constrained.

As a consequence, the technological innovations attenuated the environmental pressures created by the expansion of the agricultural frontier. The area with private native forests increased in municipalities more suitable for soybean cultivation using modern technologies. This result implies that technical change in agriculture reduced the total loss in forest induced by the expansion of the agricultural frontier. A counterfactual simulation suggests that a municipality in the 75th percentile of the agronomic potential distribution experienced an increase of 3.9 percentage points (37,700 hectares) in native forests com-

[3] Nunn and Qian (2011) is the first paper which used FAO/GAEZ data in economics while Bustos et al. (2013) propose the soybean potential measure used in this paper.

pared to a municipality in the 25th percentile of this distribution.

The model suggests that the technological innovations should increase investments in capital and modern agricultural inputs as crop cultivation is more capital-intensive than cattle grazing. The estimated impacts of technical change on capital and fertilizer use are consistent with this idea. We find that the technological innovations increase the use of tractors and the value of farm capital in municipalities more suitable for soybean cultivation. We also estimate that these innovations increase liming use and the total expenditures with fertilizers. These pieces of evidence highlight that crop cultivation is more intensive in capital and modern inputs than cattle grazing.

The economic benefits associated with the technological innovations are as relevant as the environmental benefits. The gains from the technological innovations were capitalized in higher farm and land values. A simple calculation suggests that a municipality in the 75th percentile of the agronomic potential distribution experienced a relative increase in land values of more than US$ 62 millions in the period following the technological innovations when compared to a municipality in the 25th percentile of this distribution.

The literature suggests that increases in crop cultivation in some areas of Brazil spur increases in cattle grazing in the other areas (Lapola et al., 2010; de Sá et al., 2013; Richards et al., 2014). This phenomenon which is called indirect land use change is thought to increase deforestation. Its presence can be important for interpretation of the results presented above. Our estimates might represent the combined direct effect of less deforestation in more suitable municipalities and the indirect effect of more deforestation in less suitable municipalities. However, it is important to note that this indirect effect cannot be present unless the technological innovations displace cattle grazing.

We find no evidence of displacement of cattle grazing. The number of cattle does not change in municipalities more suitable for soybean production despite the reduction in pasture area. This suggests that spillovers from the technological innovations offset the reduction in pastures. There are several possible sources of spillovers. Other farming activities can benefit from machines purchased, practices adopted and land prepared for soybean cultivation. The evidence also suggests that spillovers led to the increase of the production of maize in the region. This result is consistent with the existence of agronomic benefits of rotating land between soybean and maize cultivation (Livingston et al., 2008).

The results are robust to several specification checks. A falsification test suggests that the results are not related to the overall expansion of agriculture to areas more suitable for crop cultivation in general. Other specifications including alternative controls also suggest that changes in land tenure and access to credit are not driving the results.

The evidence from this paper contribute to a growing literature connecting environmental and development economics (Greenstone and Jack, 2013). There are some existing studies which estimate the environmental consequences of changes in agricultural production possibilities. Most existing studies suggest that deforestation increases when agricultural production possibilities improve. Foster and Rosenzweig (2003) find evidence that technical change in agriculture increases deforestation using information from Green Revolution technologies across Indian villages. Pfaff et al. (2007) and Souza-Rodrigues (2013) estimate that better transportation infrastructure increases deforestation using information from roads in the Brazilian Amazon. Our evidence contradicts these results and suggests that technical change in agriculture is not associated to increases in deforestation in some contexts. Our findings are consistent with Assunção et al. (2014) who find that electrification is associated with less deforestation in Brazil.

It is important to differentiate our results from Foster and Rosenzweig (2003). We interpret the difference in the results from these papers is related to the differences in the contexts. The adoption of High-Yielding Varieties (HYV) generated in the Indian Green Revolution is also associated with fertilizer adoption (Bardhan and Mookherjee, 2011). Nevertheless, farms in India are small and unmechanized (Foster and Rosenzweig, 2013). Therefore, capital expenditures required to adopt new agricultural technologies are much lower in India than in Central Brazil.

This paper also contributes to a small literature that investigates the determinants of the development of the Brazilian agricultural frontier during the last decades (Gasques et al., 2004; Rada and Buccola, 2012; Rada, 2013). It contributes to this literature as it provides causal evidence on the role of biological innovations to the historical agricultural expansion in Central Brazil. This evidence complements other historical studies which highlight the importance of research investments and biological innovations to agricultural development in other contexts and periods (Hayami and Ruttan, 1970; Olmstead and Rhode, 2008; Kantor and Whalley, 2013).

The remainder of this article is organized as follows. Section 2 provides background information on technological innovations and agricultural development in Central Brazil. Section 3 presents the theoretical model used to help interpret the results. Section 4 describes the data and the baseline differences among municipalities in Central Brazil. Section 5 presents the empirical framework employed in the estimates. Section 6 presents the main results and discusses their robustness. Section 7 concludes.

2 Historical Background

2.1 Incentives and Constraints to Agricultural Development until 1970

Central Brazil covers about one fifth of Brazil and is composed of four states (Goiás, Mato Grosso, Mato Grosso do Sul and Tocantins). It is mostly located in the Cerrado biome although some of its lands are in other biomes.[4] The region's soils are infertile due to a combination of soil acidity, aluminum prevalence, and nutrient scarcity. These characteristics limited occupation and agricultural development in Central Brazil until recent decades. High transportation costs to the main Brazilian cities and ports exacerbated the region's natural disadvantages and further limited its occupation and agricultural development (Guimarães and Leme, 2002; Klink and Moreira, 2002).

Industrialization and urbanization of neighboring states increased meat demand and promoted extensive cattle ranching in the region after 1920. Cattle ranching benefited from the native pastures that cover vast a substantial share of Central Brazil's land area. However, its impact on occupation and agricultural development was limited since it used little labor or modern inputs (Klink and Moreira, 2002).

Promoting occupation and agricultural development in the region became an objective of several Brazilian governments after 1940 (Guimarães and Leme, 2002). The Brazilian government aimed to promote crop cultivation in central Brazil in order to meet the growing food demand created due to a combination of urbanization and population growth (Klink and Moreira, 2002). Expanding agricultural production was considered important to ease the pressures on food prices and avoid inflation.

The government also sought to expand the agricultural frontier to foster industrialization through higher demand for farm inputs. It believed that the expansion of the agricultural frontier would increase the demand for tractors and fertilizers and help these industries to develop in Brazil. Finally, the expansion of the agricultural frontier was considered important to reduce pressures on land reform in other regions. In particular, the conservative modernization proposed after the 1964 coup sought to ease these pressures through population movements to the agricultural frontier rather than through land reform (Salim, 1986; Helfand, 1999; Houtzager and Kurtz, 2000).

Incentives for agricultural production along the agricultural frontier after 1940 included

[4]The main characteristics of the Cerrado biome are the prevalence of savannah vegetation and the tropical climate with humid summer and dry winter. Detailed information on this biome can be found in Oliveira and Marquis (2002).

both subsidies and investments in infrastructure (Klink and Moreira, 2002). The government subsidized credit and provided agricultural credit lines with negative interest rates. It also established minimum price programs to reduce risks that farmers faced when operating on the agricultural frontier. Furthermore, the government invested in road building and electrification.[5]

Government policies induced the occupation of Central Brazil after 1940. Rural population increased 3% per year from less than 1 million in 1940 to 2.6 million in 1970 despite the substantial urbanization experienced during that period in Brazil as a whole. However, the evolution of rural development was less impressive.

Table 1, Panel A illustrates the evolution in agricultural development in the region before 1970. Each column reports the variation in area and yield for a different agricultural product between 1960 and 1970. Cropland experienced a rapid increase in the decade which increased from 72.3% to 122% depending on the crop. The growth in crop cultivation was, however, associated with a substantial fall in crop yields that fell from 16% to 39% depending on the product. Pasture area also increased, although this rise was not associated with a decrease in the number of cattle per area.

Historical accounts emphasize that the fall in yields for several crops was a consequence of the increased cultivation of the region's acid and nutrient poor soils (Sanders and Bein, 1976). Crop cultivation was an intermediate stage between deforestation and cattle grazing since it helped the soil to retain nutrients. For this reason, investments in fertilizers and tractors remain limited (Klink and Moreira, 2002).

2.2 Technological Change and the Expansion of Soybean Cultivation after 1970

Adverse agro-climatic characteristics were an important constraint to agricultural development in Central Brazil. These characteristics limited cultivation of agricultural products - such as soybeans and cotton - cultivated with success in other Brazilian regions. Government investments in agricultural research started in the 1960s aiming to overcome the geographic constraints that agricultural production faced in Central Brazil (Klink and

[5]Colonization projects concentrated subsidies and investments in infrastructure (Santos et al., 2012). Colonization projects were either public or private depending on the region. These projects provided farmers with land rights and some basic infrastructure which facilitated migration and induced farmers to move to the agricultural frontier (Jepson, 2002). The first colonization projects were created in the 1940s. Subsequent projects were established in the region until the 1980s.

Moreira, 2002). These investments were inspired by the success of the Green Revolution in other developing countries.[6]

Some of these investments focused in engineering soybean varieties adapted to the tropical climate and the Cerrado biome.[7] Investments in soybean research started in the 1950s in the Instituto Agronômico de Campinas and expanded in the 1960s with the establishment of a national program that coordinated and promoted research on this crop. These investments continued to increase fast in the subsequent decade with the creation of Embrapa, the national agricultural research corporation (Spehar, 1994; Kiihl and Calvo, 2008; Cabral, 2005).

Soybean adaptation was essential for its cultivation in Central Brazil. Yields from traditional varieties in Central Brazil were lower than 1 ton per hectare (compared to yields higher than 2 tons per hectare in southern Brazil). The central issue to plant development in the region was the reduced sunlight exposition in tropical areas compared to temperate areas from which the crop originates. Another important issue was the abundance of aluminum, which is toxic to plants, in the region's soils (Spehar, 1994). Both issues impaired plant development and negatively affected the yields obtained using traditional varieties.

The investments in soybean research succeeded both in developing varieties resistant to aluminum and adapted to the tropical climate. Varieties adapted to the agro-climatic characteristics from Central Brazil were developed following the experiences of the Green Revolution elsewhere. Figure 1 reports a time line with the introduction dates of the varieties that represent the main biological innovations observed in the period.

The first varieties which could be cultivated in some Central Brazil areas were developed in 1965 and 1967. These varieties were adapted to latitudes lower than 20 degrees, enabling soybean cultivation in southern localities of the region along the states of Goiás and Mato Grosso do Sul. These varieties achieved experimental yields higher than 2 tons per hectare. Varieties more resistant to aluminum were developed in 1969 and 1973. A significant development came in 1975 with the development of the Cristalina cultivar which achieved experimental yields higher than 3 tons per hectare and could be cultivated in more localities from Central Brazil. Later developments generated in Embrapa research centers created varieties quite resistant to high aluminum levels and adapted to latitudes below 10 degrees in the states of Mato Grosso and Tocantins (Spehar, 1994; de Almeida

[6] Cabral (2005) describes the importance of the Green Revolution in other developing countries in inducing the Brazilian government to invest in agricultural research.

[7] It is unclear in the literature what motivated the Brazilian government to invest in soybean research and not in other crops.

et al., 1999). These developments complete the adaptation process.

Historical accounts suggest that the technological innovations led to a considerable expansion of soybean cultivation in Central Brazil after 1970 (Klink and Moreira, 2002). Cultivation at the beginning of the 1970s was concentrated in the region's southernmost areas as the varieties introduced in the late 1960s could not be cultivated in latitudes smaller than 10 degrees. Technological developments induced settlement and cultivation in northern Central Brazil by the end of the 1970s despite the reduction in international prices.

Table 1, Panel B illustrates the expansion of soybean cultivation. Each column reports the variation in area and yield for a different agricultural product between 1970 and 1985. Soybean cultivation increased more than 88 times in the period while its yields grew 140%. This expansion was much larger than the expansion observed either in the area or yields for the other fours agricultural products presented in the table. It should be stressed that the growth in yields in other agricultural products might reflect spillover effects from the changes in agricultural practices required to expand soybean cultivation.

The expansion of soybean cultivation induced substantial changes in agricultural practices. Rezende (2002) argues that technological innovations were essential to turn intensive agriculture viable in Central Brazil. Nevertheless, the author also argues that the expansion of crop cultivation also required significant investments in land preparation as liming and other fertilizers must be used in large amounts to fertilize soils. His calculation indicates that expenditures with liming and other fertilizers represent 42.5% of the total investments needed to prepare land for intensive agriculture. As a comparison, land acquisition represents 25% while land clearing represents 17.5% of these investments.

Investments in tractors are also required to intensive agriculture in Central Brazil. The prolonged droughts common in the region turn the use animal traction impossible as soils become too compact during the dry season (Sanders and Bein, 1976). Plowing using animal traction must begin after the end of this season. Such timing reduces water absorption as soils are still compact when it starts raining. It also pushes plowing to a period when mules and other animals are debilitated. Tractors remove these constraints with farmers being able to prepare soils during the drought.

The need for investments in fertilizers and tractors make crop cultivation more capital-intensive than cattle grazing in Central Brazil. Figure 2 illustrates this idea and reports a positive relationship between crop cultivation and the use of fertilizers and tractors across Brazilian municipalities. Panels A-B depict this relationship for 1960 while Panels C-D depict this relationship for 1970. These relationships provide further evidence that crop cultivation is more capital-intensive than cattle grazing. The relationship is the same when the sample is restricted to municipalities in Central Brazil or when we include controls for geographic characteristics.

3 Theoretical Framework

To motivate the empirical exercise, consider a farmer choosing optimal land use between pastures for cattle grazing (T_P) and cropland (T_C). The farmer incurs in a cost κ_P to use one unit of land to cattle grazing and κ_C to use one unit of land to crop cultivation. We assume that crop cultivation is more capital-intensive than cattle grazing, $\kappa_C > \kappa_P$. This assumption is consistent with the evidence that crop cultivation in Central Brazil requires intensive investments in fertilizers and machines discussed in the previous section.

Let A_P be a technological parameter for cattle grazing and A_C a technological parameter for crop cultivation. Cattle grazing output is $A_P F(T_P)$ while crop cultivation output is $A_C F(T_C)$ in which $F(.)$ is an increasing and concave production function.[8]

The farmer's profit is:

$$\Pi(T_P, T_C) = A_P F(T_P) + A_C F(T_C) - \kappa_P T_P - \kappa_C T_C \tag{1}$$

We assume that the farmer faces a capital constraint K. This constraint captures informational or institutional failures that limit access to credit. Optimal land allocation is obtained maximizing 1 subject to the capital constraint $\kappa_P T_P + \kappa_C T_C \leq K$. Let T_P^* and T_C^* denote the equilibrium land use in pastures and cropland. Also define $T_F^* = T - T_P^* - T_C^*$ as the equilibrium native forests area.

The technological innovations that adapted soybeans to Central Brazil are interpreted as an increase in the technological parameter for crop cultivation (A_C) relative to the technological parameter for cattle grazing (A_P). This increase will have an unambiguous effect on cropland:

$$\frac{dT_C^*}{dA_C} > 0 \tag{2}$$

However, the effects of these innovations on pastures and native forests depend on the

[8]Notice that we are assuming that the production function's shape is the same for cattle grazing and for crop cultivation. Results are unchanged without this assumption.

existence of capital constraints:

$$\frac{dT_P^*}{dA_C}\begin{cases} = 0 & \text{if } \kappa_P\left(\frac{\partial F}{\partial T_p}^{-1}\left(\frac{\kappa_P}{A_P}\right)\right)+\kappa_C\left(\frac{\partial F}{\partial T_C}^{-1}\left(\frac{\kappa_C}{A_C}\right)\right) < K \\ < 0 & \text{if } \kappa_P\left(\frac{\partial F}{\partial T_p}^{-1}\left(\frac{\kappa_P}{A_P}\right)\right)+\kappa_C\left(\frac{\partial F}{\partial T_C}^{-1}\left(\frac{\kappa_C}{A_C}\right)\right) \geqslant K \end{cases} \tag{3}$$

$$\frac{dT_F^*}{dA_C}\begin{cases} < 0 & \text{if } \kappa_P\left(\frac{\partial F}{\partial T_p}^{-1}\left(\frac{\kappa_P}{A_P}\right)\right)+\kappa_C\left(\frac{\partial F}{\partial T_C}^{-1}\left(\frac{\kappa_C}{A_C}\right)\right) < K \\ > 0 & \text{if } \kappa_P\left(\frac{\partial F}{\partial T_p}^{-1}\left(\frac{\kappa_P}{A_P}\right)\right)+\kappa_C\left(\frac{\partial F}{\partial T_C}^{-1}\left(\frac{\kappa_C}{A_C}\right)\right) \geqslant K \end{cases} \tag{4}$$

Appendix A.1 provides a proof of the comparative statics above. The intuition of these results is straightforward. In equilibrium, the farmer will reallocate land to crop cultivation when it becomes more productive. If there are no capital constraints, an increase in cropland will not affect pastures as there are resources available to expand agricultural activities. The expansion of cropland will be at expense of native forests in this scenario as suggested by the Jevons Paradox.

If capital constraints are binding, however, the increase in cropland will require a reduction in pastures as there are no resources available to expand agricultural activities. Moreover, since crop cultivation is more capital-intensive than cattle grazing, the farmer will need to reduce pastures in more than one hectare to increase cropland in one hectare. As a consequence, the Jevons Paradox no longer holds and the area covered with native forests will increase.

The model abstracts from positive spillover effects of the technological innovations that adapted soybeans to Central Brazil on cattle grazing. Nevertheless, the qualitative results presented in equations 2-4 are not affected as long as the impact of the technological innovations is larger in A_C than in A_P. These qualitative results are also not affected when the technological innovations generates positive spillover effects to crops such as rice and maize.

The responses predicted in the model can be tested using the technological innovations that adapted soybeans to Central Brazil. Whether the technological innovations increase or decrease deforestation can be used to assess the existence of capital constraints. Information on investments in machines and fertilizers can also be used to understand if the technological innovations are inducing farmers to substitute investments in forest clearing for investments in agricultural intensification as suggested in the model.

4 Data Construction and Baseline Differences

4.1 Data Construction

Historical municipal-level data on agricultural outcomes is drawn from the Agricultural Census. The analysis uses data from the five waves that occurred from 1960 to 1985. The initial waves (1960 and 1970) depict agricultural outcomes before soybean adaptation. The following waves (1975 and 1980) depict agricultural outcomes during soybean adaptation while the last wave (1985) depicts agricultural outcomes after soybean adaptation. The Agricultural Census data from 1970 to 1985 was obtained in digital format. The Agricultural Census from 1960 was digitized from the original manuscripts. The main variables of interest are land use, agricultural production, input use, total expenditures and farm values (land and capital). Data on expenditures and farm values is deflated to 2012 using the methodology proposed in Corseuil and Foguel (2002).[9]

To account for border changes and the creation of municipalities, we use the definition of minimum comparable areas from the Brazilian Institute of Applied Economic Research (IPEA). The minimum comparable areas make spatial units consistent over time. The estimates use a minimum comparable areas definition that makes spatial units consistent with the existing municipalities and borders from 1960.[10] That leaves 193 spatial units that can be compared across periods. We refer to these minimum comparable areas as municipalities throughout the paper.

The empirical design estimates whether agricultural outcomes changed differentially in municipalities that benefited more from the technological innovations that adapted soybeans to Central Brazil. We measure the soybean potential using modern technologies with data from the Food and Agriculture Organization (FAO) Global Agro-Ecological Zones (GAEZ) database. The database uses an agronomic model that combines geographical and climatic information to predict potential yields for several crops under different levels of input use. Input use varies from low (corresponding to traditional agricultural practices) to high (corresponding to commercial agriculture using machines and chemi-

[9]The series containing the PNAD deflator starts in 1976. We use the consumer price index from the Brazilian Census Bureau to calculate the deflator for 1975. This price index is the same used in the methodology proposed in Corseuil and Foguel (2002) to construct the deflator for other years. It should be noted that the choice of deflator is irrelevant for the estimates since we use year fixed effects.

[10]There were 243 municipalities in Central Brazil in 1960, 303 municipalities in Central Brazil in 1970 and 366 municipalities in central Brazil in 1985. The minimum comparable areas from IPEA are constructed in a conservative fashion that aims to make borders compatible through time.

cals). The data is reported in 0.5 degrees by 0.5 degrees grid cells.[11]

Following Bustos et al. (2013), we define the soybean potential using modern technologies as the difference between the potential yields of the high and the low input regimes. This measure assumes that variation in soybean productivity across municipalities after the technological innovations is associated with variation in agronomic potential using modern inputs (tractors and fertilizers). It also assumes that variation in soybean productivity before the these innovations is related to agronomic potential using no modern inputs. The measure captures the relative gain that a farmer could obtain shifting land use to soybean after its adaptation to Central Brazil.

The main limitation of the GAEZ database is that the agronomic model which underlies it uses contemporaneous information on technologies to measure agricultural potential for each crop. Therefore, we are assuming that technological change after the period analyzed did not affect comparative advantage to cultivate soybeans across Central Brazil.[12] Although a restrictive assumption, we can validate it using data on soybean adoption. We should not observe a positive correlation between soybean adoption and potential if technological change after the sample period affected comparative advantage. We return to this issue when we present the estimates.

We construct the soybean potential measure in three steps using the ArcMap software. First, we superimpose the map on potential soybean yields in different input regimes and the map of municipalities. Second, we calculate the average potential yield of all cells falling within each municipality both for the potential soybean yields in the low and the high input use. Third, we calculate the soybean potential in each municipality as the difference between the average soybean potential yield in these regimes.

The agronomic potential measure is normalized to facilitate the interpretation of the estimates. We subtract each value of agronomic potential by the its sample mean and divide the resulting value by the standard deviation to obtain a variable with mean zero and standard deviation one. Figure 3 maps soybean potential across Central Brazil. Darker municipalities have higher soybean potential while lighter municipalities have lower soybean potential using modern technologies. Municipalities in southern areas present higher soy-

[11]The GAEZ database was introduced in the economics literature by Nunn and Qian (2011) who investigate the effect of the introduction of potatoes in urbanization in Europe. This database was subsequently used in a number of papers such as Costinot et al. (2014) who investigate the impact of climate change in agriculture, Bustos et al. (2013) who investigate the impact of Genetically Engineered (GE) crops on agriculture and industrialization in Brazil and Marden (2014) who investigates the impact of agricultural reforms on agriculture and industrialization in China.

[12]A similar assumption is made in Costinot and Donaldson (2011).

bean potential.

The empirical design uses geographic and socioeconomic information to control for differences across municipalities that can be correlated both with the evolution of agricultural outcomes and soybean potential. Geographic characteristics included are latitude (linear and quadratic term) and longitude (linear and quadratic term), distance to Brasília (linear and quadratic term), and distance to the coast (linear and quadratic term). These variables control for differences in the evolution of the agricultural frontier (expanding to the north across periods) and for differences in transportation costs (falling over time due to road construction). We calculate the geographic controls using the ArcMap software.

Socioeconomic characteristics included are the initial population density, private and state-owned bank branches per area, number of farms per area, and average farm size. Initial population density is calculated using the Population Census, the number of bank branches per area is calculated using historical data from the Brazilian Central Bank and the other variables are computed using data from the Agricultural Census. Population per area control for differences in the evolution of agricultural outcomes that area correlated with historical settlement patterns across the sample municipalities. Bank branches per area control for the effect of policies driving the expansion of bank branches in the region in the period on agricultural outcomes. These policies expanded a lot access to agricultural credit and affected both private bank branches (since private banks should open branches in remote localities to be able to expand in central localities throughout most of the period) and state-owned banks (since these banks expanded a lot during the period) (Graham et al., 1987; Helfand, 1999; Gasques et al., 2004). Number of farms per area and average farm size control for the effect of differences in land distribution on agriculture. Colonization projects are a characteristic of the expansion of the Brazilian agricultural frontier in the period and were an important determinant of land distribution in frontier municipalities (Alston et al., 1996; Jepson, 2002). Therefore, it is important to control for the influence of these projects on the evolution of the number of farms and the average farm size.

Appendix A.2 describes in detail the data sources used and the definition of each variable.

4.2 Descriptive Statistics and Baseline Differences

Figure 4 shows that there were substantial aggregate changes in land use in Central Brazil during the period 1960 to 1985. Panel A reports that the expansion of the agricultural frontier increased total farmland from 32 percent to 62 percent of the total municipality area. Changes in land use accompanied the increase in farmland. Since there is no land use information from satellite data for the period, these aggregate changes refer to the evolution in land use in private land. This is important for the interpretation of the aggregate trends and the estimates. We return to this issue in the remaining of the paper.

Panels B and C provide evidence that farmers converted incorporated land in cropland and cultivated pastures. Cropland area increased from less than 1 percent to 5 percent of the total municipality area from 1960 to 1985. The area with cultivated pastures also increased fast from less than 5 percent to more than 15 percent of total municipality area during the same period. In both cases, the expansion became faster after 1975. Panel D reports that farmers also expanded the area with cultivated forests. The increases area concentrated in the period 1970 to 1980. Notice, however, that the total area with cultivated forests continued to be irrelevant.

Farmland expansion creates a mechanical increase in the areas covered with native pastures and forests located in private land. The evolution of these land use categories will reflect this mechanical effect as well as the conversion of natural pastures and forests into cropland and cultivated pastures. Panel E provides evidence that the area with native pastures increased from 1960 to 1970. It then stagnated until 1975 and started decreasing afterwards. Panel F reports that the area with native forests increased from 1960 to 1980 and stagnated between 1980 and 1985.

Figure 5 presents aggregate changes in the allocation of cropland in the period 1960 to 1985. Panel A reports the expansion of soybean cultivation. It started to increase in 1970 and it to grew much faster after 1975. We interpret this increases as a consequence of soybean adaptation and the agricultural adjustment to it.

Panel B depicts the evolution of rice cultivation in Central Brazil in the period. Rice was the most important crop in the region before the technological innovations. Its cultivation expanded until 1980, but decreased afterwards. Historical accounts relate the expansion in rice cultivation throughout the 1970s to soybean expansion. Farmers switching to crop cultivation started to cultivate rice - for which adapted varieties were available - while learning to cultivate soybeans (Jepson 2006). The observed decline in rice production after 1980 might be related to its substitution by soybeans as learning ended.

Panels C and D report the changes in maize and sugarcane cultivation across the sample periods. Cultivation also expanded for these crops. This expansion might reflect positive spillovers from investments in land preparation and machines for these crops cultivation.

The increase of maize cultivation can also reflect the agronomic benefits from rotating land between soybean and this crops documented in the literature (Livingston et al. 2008).

The aggregate changes in land use described above are essential to interpret the empirical estimates. The expansion of the agricultural frontier was creating environmental pressures in Central Brazil. What we estimate is whether the technological innovations that adapted soybeans to the region increased or reduced these environmental pressures.

The empirical design uses the potential to cultivate soybeans using modern technologies as a proxy for the impact of the technological innovations. An important issue is whether municipalities with higher and lower soybean potential were different before the technological innovations took place. Table 2 reports the baseline differences in agricultural outcomes among municipalities with higher and lower potential to cultivate soybeans using modern technologies.

Column 1 reports the average municipality characteristics in 1960. Column 2 presents the bivariate relationship between each agricultural outcome in the baseline and soybean potential. Columns 3 reports the within-state relationship between these variables. Column 4 depicts the same relationship including geographic characteristics as controls. Variables included are latitude (linear and quadratic term) and longitude (linear and quadratic term), distance to Brasília (linear and quadratic term), and distance to the coast (linear and quadratic term).

Prior to the technological innovations, municipalities that benefited more from the technological innovations presented higher agricultural development. The controls included attenuate these differences, but some differences persist. Panel A reports that municipalities more suitable for soybean cultivation using modern technologies had more cropland and cultivated pastures and less native forests. Panel B provides evidence that these municipalities also produced more rice and maize. Panel C indicates that agriculture in these municipalities were more intensive in tractors and fertilizers while Panel D reports that farm and land values were higher on average.

The existence of these baseline differences is the main empirical challenge to the empirical design. To the extent that agricultural outcomes changed differentially in municipalities with higher initial agricultural development, our empirical estimates might confound the impact of the technological innovations with these differential trends. The main specifications include geographic characteristics, state dummies and the initial value of agricultural outcomes from Table 2 interacted with time dummies as controls to overcome this challenge. The baseline characteristics control for the existence of differential trends related to these agricultural outcomes.

The main analysis also includes socioeconomic characteristics to control for other policies and changes affecting agriculture in the period. Socioeconomic characteristics included are the initial population density, private and state-owned bank branches per area, number of farms per area, and average farm size. These variables control for the effect of historical settlement patterns and government policies affecting credit and land distribution in the sample period. Data from the periods before the technological innovations is used to assess whether changes in outcomes across municipalities more and less suitable for soybean cultivation using modern technologies were similar before the technological innovations.

5 Empirical Framework

The empirical analysis combines time variation with cross-sectional variation in agronomic potential to cultivate soybeans using modern technologies. It estimates changes in agricultural outcomes between municipalities more and less suitable soybean cultivation relative to the baseline, conditional on a set of covariates. Estimates use a balanced sample of municipalities located in Central Brazil and are based on the following estimating equation:

$$Y_{mst} = \alpha_m + \delta_{st} + \sum_{v=1970}^{1985} \beta_v (Soybean\ Potential_m * I_v) + \sum_{v=1970}^{1985} (\mathbf{X}_m * I_v)\mathbf{\Gamma}_v + u_{mst} \qquad (5)$$

where Y_{mst} is an agricultural outcome in municipality m in state s in time t; α_m is a municipality fixed effect; δ_{st} is a state-time fixed effect; $Soybean\ Potential_m$ is the soybean potential measure; I_v is a year indicator; $\mathbf{X}_m$ is a vector of municipality characteristics; and u_{mst} is an error term. The coefficients of interest are the four β_v.

The municipality fixed effects control for time-invariant characteristics of the municipalities which might be correlated with soybean potential. The interaction between state and period dummies controls for state-specific shocks in each of the four states included in the sample.[13] The other covariates control for government policies affecting access to credit and land distribution, historical settlement patterns and the evolution of the agricultural

[13] It is important to note that there were only two states in central Brazil in the beginning of the period under analysis. Mato Grosso and Mato Grosso do Sul split in 1975 and Goiás and Tocantins split in 1989. However, we include state-year fixed effects considering the four states that currently exist on the assumption that the important differences that exist across these states were already relevant in the earlier period.

frontier. These covariates also allow municipalities with different baseline characteristics to present different changes in outcomes after 1960. For instance, municipalities with more cropland in the baseline are permitted to experience different changes in agricultural outcomes across the sample periods.

The identification assumption is that – within a state and in the absence of soybean adaptation – the changes in agricultural outcomes would have been the same in municipalities more and less suitable for cultivate soybeans with similar geographic and socioeconomic characteristics. This assumption is the equivalent of the parallel trends assumption from differences-in-differences strategies. The difference is that it must hold within municipalities located in each state and not across municipalities located in different states. It also must hold after controlling for differential changes that are correlated with either the geographical or baseline characteristics included in the empirical analysis.

The coefficient associated with 1970 (β_{1970}) tests whether agricultural outcomes presenter similar changes before the technological innovations that adapted soybean to Central Brazil started to influence agriculture. Therefore, it is a useful test of the identification assumption. The coefficients associated with 1975 and 1980 (β_{1975} and β_{1980}) estimate the impact of these technological innovations during the adaptation process. The coefficient associated with 1985 (β_{1985}) assesses the effect of the technological innovations after the adaptation process ended.

There are two important estimation details which are worth mentioning. First, all estimates are weighted by municipality area to estimate the average effect of the technological change per hectare. Second, all reported standard errors are clustered at the municipality level to adjust for heteroskedasticity and serial correlation within municipalities.

6 Results

6.1 Soybean Cultivation and Production

Figure 6 reports the absolute changes in soybean adoption across municipalities in different percentiles of the soybean potential distribution. It uses the coefficients estimated using equation 5 to simulate the changes in soybean cultivation and production in municipalities in the 25th and 75th percentiles of the agronomic potential distribution. Estimates include the full set of controls presented in the previous section.

Panels A and B plot the changes for soybean cultivation as a share of the municipality area and as a share of cropland area. Panels C and D plot the changes in soybean production per 100 hectares of municipality area and 100 hectares of cropland. Normalizing cultivation and area using total area and cropland area is useful to understand the effects of the technological innovations on adoption both in the extensive and intensive margin.

The figure provides evidence that soybean cultivation and production was not increasing faster in municipalities more suitable for soybean cultivation using modern technologies before the introduction of these technologies in the 1970s.[14] This result lends support to the parallel trends assumption discussed earlier.

After the technological innovations, municipalities more suitable for soybean cultivation became more intensive in soybean cultivation (Panels A and B) and production (Panels C and D) than municipalities less suitable for it. This result evidences that comparative advantage to cultivate soybeans in central Brazil did not change after the sample period and validate the use of the soybean potential measure throughout the empirical design. The results for soybean cultivation and production normalized by cropland also indicate that cultivation and production increased faster than the cultivation and production of other crops. This evidence supports the idea that we are capturing the effect of technological innovations in a particular plant (as opposed to the impact of technological innovations in crop cultivation in general).

The increases in soybean cultivation and production in municipalities in the 75th percentile compared to municipalities in the 25th percentile of the soybean potential distribution are concentrated after 1975. This timing is consistent with the gradual evolution of the varieties that could be cultivated in Central Brazil. It is also consistent with the existence of substantial switching costs that prevent immediate land reallocation following the technological innovations. We discuss these switching costs in detail when presenting results on land and input use.

The timing of the increase in soybean cultivation and production suggests that international soybean prices did not drive the estimates. The collapse in the fish flour production (another important source of animal protein) led to a large increase in international prices at the beginning of the 1970s. However, international prices decreased fast in the late 1970s and continued stable at the beginning of the 1980s. Therefore, it is unlikely that the

[14]The 1960 Agricultural Census reports cultivation and production information for the most important crops in a state. Thus, there are no information on soybean cultivation or production in Central Brazil as production was irrelevant or nonexistent. We assume that production and cultivation was zero in this sample period.

expansion observed in Figure 6 is related to changes in the international prices.

Table 3 reports numerical results from estimating equation (5). Column 1 reports estimates using soybean cultivation as the share of the municipality area as the dependent variable. Municipalities more suitable for soybean cultivation using modern technologies experience significant increases at the 95% level in the area cultivated with soybeans in 1980 and 1985. The magnitude of the estimates is substantial: an increase in one standard deviation in agronomic potential led to a relative increase in soybean cultivation of 0.8 percentage points (7,800 hectares) from 1960 to 1980 and 1.4 percentage points (13,600 hectares) from 1960 to 1985.

Column 2 reports estimates using the share of total farmland cultivated with soybeans as the dependent variable. These estimates provide evidence that the technological innovations led to an increase in crop allocation to soybean cultivation. Estimates are large both in 1980 and 1985. The coefficient for 1980 is imprecise and not significant at the usual statistical levels (the p-value is 0.11) while the coefficient for 1985 is significant at the 5% level. An increase in one standard deviation in agronomic potential led to a relative increase in 9.9 percentage points in the share of cropland cultivated with the crop from 1960 to 1985. This large reallocation of cropland provides evidence of the growing importance of the soybeans in Central Brazil.

Column 3 reports estimates using the production per 100 municipality hectares as the dependent variable. This estimate also suggests a positive effect of the technological innovations that adapted soybeans to Central Brazil for this crop production. One standard deviation increase in agronomic potential led to a rise in soybean production of 1.35 tons per 100 hectares in the period 1960 to 1980 and about 2.62 tons per 100 hectares in the period 1960 to 1985.

Column 4 reports estimates using the production per 100 cropland hectares as the dependent variable. This estimate also suggests a positive effect of the technological innovations that adapted soybeans to Central Brazil for this crop production. The impact of the technological innovations in production was substantial both in 1980 and 1985. However, the coefficient for 1980 is imprecise and not significant at the usual statistical levels (the p-value is 0.12). The coefficients suggest that one standard deviation increase in agronomic potential led to a rise in soybean production of 6.03 tons per 100 hectares in the period 1960 to 1980 and about 18.19 tons per 100 hectares in the period 1960 to 1985.

It is interesting to note that the effects estimated in Table 4 suggest that soybean yields are increasing. We can rescale the coefficients in Table 3 to obtain the impact of the technological innovations in terms of hectares (columns 1 and 2) and harvested tons (columns 3 and 4). Then we can compare the coefficients in columns 1 and 3 or columns 2 and 4 to get an estimate of the innovations' effect on yields. This "back-of-the-envelope" calculation indicates that one standard deviation increase in agronomic potential led to a rise of more than 70% on the average soybean yield.

6.2 Land Use

Figure 7 depicts the absolute changes in land use across municipalities in different percentiles of the soybean potential distribution. It uses the coefficients estimated using equation (5) to simulate the changes in land use in municipalities in the 25th and 75th percentiles of the agronomic potential distribution. The figure reports the simulated changes in land use for total farmland, cropland, native pastures, and native forests.

Panel A provides evidence that total farmland expanded in the same magnitude across the indicated percentiles. Although the theoretical model does not consider explicitly the farmer's choice to expand farmland, it is possible to interpret this result in light of the theory. The model predicts that technological innovations will increase total land use when farmers are not capital constrained and decrease it when farmers are capital constrained. We expect farmland to grow in the former case, but not in the latter. Therefore, the evidence that the technological innovations do not change total farmland is suggestive evidence that capital constraints are binding.

Moreover, the absence of effect of the technological innovations on total farmland makes the identification of the environmental externalities associated with the technological innovations easier. Information on land use is restricted to information about land use in the existing farmland since there is no satellite data on land use for most of the period. These data restrictions often require additional assumptions on land coverage outside the existing farmland. Nevertheless, the absence of effect of the technological innovations on total farmland makes possible to infer the environmental externalities using the available data without restrictive assumptions.

Panel B reports that native forests expanded at a faster rate in municipalities more suitable for soybean cultivation using modern technologies. This evidence suggests that the technological innovations are associated with environmental benefits. As described in the theoretical model, technological innovations will create environmental benefits when crop cultivation is more capital-intensive than cattle grazing and capital constraints are binding. Therefore, this result is a evidence that farmers are capital constrained.

Panel C reports that cropland expanded at a faster rate in municipalities more suitable for soybean cultivation using modern technologies. We estimate no increase in cropland in municipalities more suitable for soybean cultivation in 1970. Cropland started to rise faster in these municipalities in 1975. The difference in cropland in municipalities in the 75th and the 25th percentile became larger in 1980 and 1985. These findings are consistent with the theoretical model prediction that cropland should increase as a result of the technological innovations regardless the existence of capital constraints.

Panel D provides evidence that the expansion of cropland is associated with a reduction in native pastures. Native pastures decline in municipalities more suitable for soybean cultivation in particular in the later sample periods. This evidence further suggests that farmers are capital constrained and have to reduce pastures to increase cropland. Notice that the decline in pastures is larger than the increase in cropland which results in the increase in forests.

Table 4 reports the numerical results from estimating equation (5) for the same outcomes presented in Figure 7. It also reports estimates using the cultivated pastures and forests as additional dependent variables. Column 1 reports the estimates obtained using the share of farmland as the dependent variable. Coefficients are close to zero and not significant at the usual levels across all sample periods. There is no definite pattern in point estimates that switch between being positive and negative across periods.

Column 2 reports that the area with native forests in municipalities more suitable for soybean cultivation after 1970. The coefficients are significant at the 10% level in all periods after the technological innovations. The magnitude of the environmental benefit that the technological innovations generate is substantial. An increase in one standard deviation in agronomic potential is associated with a relative increase of 2.3 percentage points (22,300 hectares) in the share of native forests between 1960 and 1975 and 2.1 percentage points (20,300 hectares) between 1960 and 1980. It is also associated with a relative increase of 2.9 percentage points (28,100 hectares) between 1960 and 1985. These estimates suggest that a municipality in the 75th percentile of the agronomic potential distribution experienced a increase in 3.8 percentage points (36,400 hectares) in native forests when compared to a municipality in the 25th percentile of this distribution. This result implies that the technological innovations eased the pressure on forests that the expansion of the agricultural frontier generated.

Column 3 provides evidence that the technological innovations are associated with positive and significant relative increases in cropland after 1970. The magnitude of the estimated coefficients is large and implies that an increase in one standard deviation in agronomic potential is associated with a relative increase in 1.2 percentage points (11,700 hectares) in the share of cropland between 1960 and 1975, an increase of 1.5 percentage points (14,500 hectares) between 1960 and 1980, and an increase of 2.2 percentage points (21,300 hectares) between 1960 and 1985. The estimates translate in a rise in cropland of 2.8 percentage points (27,600 hectares) during the period 1960 to 1985 in a municipality in the 75th percentile of the agronomic potential distribution compared to a municipality in the 25th percentile of the same distribution.

Notice that we do not estimate a positive effect of the technological innovations on soybean cultivation in 1975. However, we estimate a positive impact of these innovations on cropland in this period. To reconcile these estimates, it is important to highlight that farmers started cultivating rice before moving to soybean cultivation (Jepson, 2006). Rice cultivation was easier as aluminum-resistant varieties were available. Thus, it was an important source of revenue while farmers were experimenting with soybean varieties. Furthermore, it helped to fertilize and prepare the soil for soybean cultivation and can be regarded as an investment in land preparation.

The evidence points out that the increases in cropland continue to be larger than the increases in soybean cultivation in the later periods. The difference in magnitudes is consistent with the idea that soybean adoption generated positive spillovers to other crops. We discuss these spillover effects later.

Column 4 reports that the relative increase in cropland is associated with a relative decrease in the area with native pastures in municipalities more suitable for soybean cultivation. Estimates are negative in all periods and increase in absolute value across time. Nevertheless, the estimates are significant at the 5% level only in the last sample period. The decline in native pastures more than offset the increase in cropland. An increase in one standard deviation in agronomic potential is associated with a relative decrease in 5.0 percentage points (48,500 hectares) in native pastures. This estimate translates in a decline in native pastures of 6.5 percentage points across municipalities in the 75th and 25th percentile of the agronomic potential distribution during the period 1960 to 1985.

Column 5 provides evidence that the technological innovations are not associated with relative changes in the cultivated forests. Column 6 reports that there are no differential changes in cultivated pastures in municipalities more suitable for soybean cultivation. Columns 4-6 provide evidence that the technological innovations reduced total land use for agricultural production (cattle grazing and crop cultivation). There were no changes in cultivated pastures (column 6) and cultivated forests (column 5) while decline in pastures (column 4) was larger than the increase in cropland (column 3). The area with native forests increased as the result of this reduction in total land use (column 2).

6.3 Agricultural Adjustment: Capital and Fertilizers

Figure 8 plots the absolute changes in capital and fertilizer use across municipalities in different percentiles of the soybean potential distribution. It uses the coefficients estimated using equation (5) to simulate the changes in land use in municipalities in the 25th and 75th percentiles of the agronomic potential distribution. The figure reports the simulated changes for four outcomes: tractors per 100 hectares of municipality area, value of capital per 100 hectares of municipality area, expenditures with fertilizers per 100 hectares of municipality area, and the share of farms using liming.[15]

Panel A provides evidence that tractor use started to increase faster in municipalities more suitable for soybean cultivation using modern technologies after 1970. The difference between the 75th and the 25th percentile increases across periods. The findings are consistent with crop cultivation being more intensive in tractors than cattle grazing. Tractor use increased as farmers reallocated land from pastures to cropland. Notice that, as in the case of cropland, expansion in tractor use occurs before the expansion in soybean cultivation. This pattern is consistent with historical accounts and suggesting that substantial investments in land preparation occurred before soybean adoption.

Panel B reports that the value of farm capital increased slightly faster in municipalities more suitable for soybean cultivation in the later sample period. The increase is, however, small compared to the overall growth in the value of farm capital.

Panel C reports that the expenditures with fertilizers increased faster in municipalities more suitable for soybean cultivation following the technological innovations. There were some differences in these expenditures between municipalities in the indicated percentiles in 1975. However, the differences grew in the later periods. These findings highlight the importance of investment in fertilizers to turn large scale commercial agriculture viable in Central Brazil.

Panel D provide similar evidence using liming use as an alternative measure of fertilizer

[15] In a companion paper, Bragança et al. (2014) evaluate the impact of the technological innovations on labor use. The evidence shows that the technological innovations increased the demand for skilled labor.

use. Liming is the most important fertilizer for intensive agriculture in Central Brazil as it is essential to reduce soil acidity. Different from the previous panel, liming use did not increase in more suitable municipalities in 1975. Nevertheless, the observed pattern is similar in the other sample periods.

Table 5 reports the numerical results from estimating equation (5) using capital and fertilizer use as dependent variables. There are no differential changes in capital and fertilizer use between 1960 and 1970. Capital use starts to increase faster in municipalities with more suitable for soybean cultivation after 1970. Farmers in more these municipalities start using more tractors (column 1) which translates into higher value of farm capital (column 2). The magnitude of these estimates is substantial. An increase in one standard deviation in agronomic potential was associated with a relative increase in 0.025 tractors per 100 municipality hectares and R$ 12,809 in the value of farm capital per 100 municipality hectares in 1985. These impacts are larger than these variable means in the baseline (0.001 and R$ 5,061).

There are also substantial increases in fertilizer use. Total expenditures with fertilizers increases starting in 1975 while the share of farms using liming – which is essential for crop cultivation in acid soils such as the ones from Central Brazil – increases beginning in 1980. Between 1960 and 1985, an increase in one standard deviation in soy potential is associated with a relative increase in R$ 1,419 in expenditures with fertilizers per 100 municipality hectares and in 2.8 percentage points in the share of farms using liming. As with the coefficients associated with capital use, the magnitude of the estimated coefficients is substantial as the baseline values for these variables were quite small.

The positive effects of the technological innovations on capital and fertilizer use are consistent with the historical accounts that argue that tractor and fertilizer adoption were essential for crop cultivation across Central Brazil (Rezende, 2002). These results also indicate that crop cultivation is more intensive in these inputs than cattle ranching. Therefore, the technological innovations and the consequent cropland expansion induced the intensification of agricultural practices.

Intensification leads to higher capital expenditures which are needed either to acquire tractors or to purchase fertilizers. To the extent that farmers are capital constrained, these capital expenditures force farmers to reduce investments in land clearing to invest in capital and fertilizers. Therefore, the results presented above are consistent with capital constraints making the technological innovations to induce farmers to switch from expansion in the extensive margin to expansion in the intensive margin as suggested by the theoretical model.

6.4 Spillover Effects

An important issue for interpretation of the estimates is the presence of indirect land use change. The literature on deforestation in Brazil emphasizes that increases in crop cultivation in some areas of Brazil spur increases in cattle grazing in other areas (Lapola et al., 2010; de Sá et al., 2013; Richards et al., 2014). This indirect land use changes is tied to the displacement of cattle grazing from areas in which crop cultivation is expanding. This displacement might increase cattle prices, creating incentives for farmers to clear forests for cattle grazing.

Our estimates might represent the direct effect of less deforestation in more suitable municipalities and the indirect effect of more deforestation in less suitable municipalities for soybean cultivation to the extent that this mechanism was relevant in our context. Previous results point out that the area with pastures decline in more suitable municipalities. This result suggests that indirect land use might be an important issue for interpretation. Nevertheless, it is important to investigate the effects of the technological innovations on cattle production since spillovers from the investments that technological innovations induce can affect pastures' output per area.

The positive spillovers from the technological innovations can come from several mechanisms. Other farming activities can benefit from the machines purchased to cultivate soybeans. It can also benefit from the experience that farmers acquire in handling machines and fertilizers. Moreover, investments in land preparation can benefit other activities since the land prepared for soybean cultivation can be used as pasture or to cultivate different products in other periods.

Table 6, column 1 provides evidence that the technological innovations did not reduce cattle production. The number of cattle per area did not decrease in municipalities more suitable for soybean cultivation. Point estimates are even positive (but standard errors are large). These estimates represent the total impact of the reduction in native pastures (direct effect) and the improvements in agricultural practices (spillover effect) on cattle grazing. Either pastures converted to cropland had small marginal benefits to farmers or spillovers from improved agricultural practices compensate the reduction in pastures. Both mechanisms suggest that there was no displacement of cattle production from more to less suitable municipalities. This ensures that the indirect land use change does not affect the interpretation of the effect of the technological innovations on deforestation.

Columns 2 to 4 from Table 6 investigate the presence of spillover effects of the technoloigcal innovations for crop production (maize, rice and sugarcane). Previous estimates indicate that spillovers for crop production might be substantial. The impact of the technological innovations on cropland (Table 4, column 3) is larger than its effect on soybean cultivation (Table 3, column 1).

Column 2 provides evidence of positive spillover effects from the technological innovations on maize production in 1980 and 1985. Both agronomic and economic research have estimated that rotation between maize and soybeans is associated with substantial benefits to soils Livingston et al. (2008). These benefits induce farmers to expand maize cultivation along with soybean cultivation and lead to a positive spillover effect. Comparing the coefficients of column 2 from Table 6 and column 3 from Table 3, we find that one unit increase in soybean production is associated with about a 0.4 increase in maize production both in 1980 and 1985. The similar magnitude evidences that there is a stable connection between these products' production. This suggests that the relationship between the production of these crops operates through the agronomic benefits of crop rotation.

Column 3 suggests some mild positive spillover effects from the technological innovations in rice production both in 1975 and 1980. These spillovers are consistent with historical accounts suggesting that farmers switching to soybeans cultivated rice during the initial growing seasons. Rice output was more predictable as experimentation with varieties was not needed. Rice cultivation also helped to fertilize land as it fixed nitrogen in the soil (Jepson, 2006). Farmers experimenting with soybeans often cultivated rice until experimentation ended and soybean output became predictable. Consistent with these accounts, these spillover effects became smaller and not significant at the usual statistical levels in 1985 when the soybean production had already increased substantially.

Column 4 shows that sugarcane production did not change differentially in municipalities more suitable for soybean cultivation. This result suggests that spillovers are not operating through cultivation of permanent crops. Nevertheless, spillovers to permanent crops might appear in the long run as fertilizers and crop cultivation help soils to fix nutrients and increase its productivity Spehar (1994).

6.5 Land Values

Table 4 estimates the relative changes in total and land values following the technological innovations that adapted soybeans the agro-climatic characteristics from Central Brazil. Consistent with the identification assumption, neither farm nor land values increased faster in municipalities more suitable for soybean cultivation between 1960 and 1970. Columns 1 and 2 provide evidence that both total and land values started to grow in these municipalities after 1975. Point estimates are imprecise for 1975 with p-values being 0.15 for total farm value and 0.11 for land values. Point estimates are significant at the 5% level in 1980 and increase in relation to the previous period. Point estimates remain constant for total farm values and decrease for total land values in 1985 in relation to 1980. The standard errors are large and estimates in 1985 are significant at the 10% level, but not at the 5% level.

Our interpretation is that farm and land values in 1980 incorporated the expected increase in agricultural rents due the technological innovations. The fall in the point estimates of land values in the subsequent period might reflect changes in macroeconomic conditions that made farm values less related to agricultural rents (Assunção, 2008). Data on agricultural revenues would help to understand this effect as rents and revenues rise by the same percentage when production is described by a Cobb-Douglas production function. Nevertheless, this data is not available in the earlier periods. Moreover, the evidence suggests that the agricultural production might not fit a Cobb-Douglas production function as farmers are changing land allocation to farm products with different input intensities.

The magnitude of the gain in farm and land values in more suitable municipalities is substantial. An increase in one standard deviation in soybean potential is associated with a rise of R$ 105 millions (US$ 48 millions) in total farm values and of R$ 73 millions (US$ 33 millions) in total land values. These coefficients translate in a relative increase of R$ 137 millions (US$ 62 millions) in farm values and R$ 92 millions (US$ 42 millions) in land values in a municipality in the 75th percentile of the agronomic potential distribution compared to a municipality in the 25th percentile of the same distribution. Overall, these results suggest that the technological innovations that adapted soybeans to Central Brazil created substantial economic benefits. The effects of the technological innovations appear to have be incorporated in farm values in 1980 as the adaptation process was completed at the end of the 1970s. Production continued to increase after 1980 as agriculture is characterized by the existence of relevant switching costs that prevent immediate land reallocation (Olmstead and Rhode, 2008; Hornbeck, 2012; Bazzi et al., 2014).[16]

Columns 3 and 4 provide evidence changes in input use capture the economic gains from the technological innovations. The effect of the innovations on farm and land values decreases and becomes insignificant once we add expenditures with fertilizers and number of tractors as controls. This suggests that input use responses are essential for farmers to benefit from the technological innovations. This is consistent with previous discussion on the importance of investments in fertilizers and tractors in the context studied. This mechanism forces capital-constrained farmers to invest less in forest clearing to be able to finance these investments, resulting in the environmental externalities documented in this paper.

6.6 Falsification Test

The identification assumption is that – conditional on the fixed effects and controls – there would be no differential changes in agricultural outcomes in the absence of the technological innovations. The main results provide evidence supporting that the changes in agricultural outcomes before the technological innovations were similar across municipalities in Central Brazil. This is suggestive evidence that the assumption described above is valid.

However, unobserved changes in determinants of agricultural development can still bias the estimates to the extent that these changes are correlated with the soybean potential measure. For instance, suppose that municipalities more suitable for soybean cultivation can be municipalities more suitable to agriculture in general. Also assume that the expansion of the agricultural frontier and government policies had a higher effect on municipalities more suitable to agriculture in general. In this scenario, the estimates presented so far would confuse the effects of the technological innovations with the effects of other determinants of agricultural development.

Therefore, it is important to provide evidence that the estimates are not capturing the effects of agricultural development in general (as opposed to the technological innovations). We implement a simple falsification test to rule out this possibility. We replace the soybean potential measure by an alternative measure capturing overall agricultural potential. We consider the soybean potential under the low input use as this measure. The idea is

[16] The evidence in Bragança et al. (2014) indicates that labor migration was an important channel to mitigate these switching costs.

that soybean potential under low input captures the crude agricultural potential of the municipalities in Central Brazil.

Table 8 reports the results of the falsification test for five agricultural outcomes. Columns 1-3 estimate the falsification test for land use measures. Column 1 reports the results using total farmland as the dependent variable, column 2 using share of cropland as the dependent variable and column 3 the share of native pastures as the dependent variable.

The evidence indicates that total farmland did not increase faster in municipalities with higher agronomic potential according to this alternative measure. This result is similar to the one obtained in the main estimates. However, the changes in cropland and native pastures are quite different from the main estimates. Cropland decreased in more suitable municipalities according to this alternative measure. The coefficients are significant at the usual levels for 1970 and 1975 and not in the later periods. There also is no clear pattern in the changes in native pastures. The coefficients are positive in 1970 and 1975 and close to zero in the later periods. Nevertheless, the coefficient is significant at the 5% level only in 1975.

Table 8, columns 4 and 5 estimate the falsification test for tractor and fertilizer use measures. Again, the results are quite different from the main estimates. Tractor use decreased in more suitable municipalities according to this alternative measure. Liming use, on its turn, did not change differentially in more suitable municipalities.

Overall, the results suggest that the main estimates did not capture the differential effect of the expansion of the agricultural frontier in municipalities with higher agronomic potential in general. This evidence provides further support to the empirical design.

7 Conclusion

Although being essential to promote agricultural development, technical change in agriculture has a controversial effect on deforestation. There is hope that technological innovations decrease deforestation as it enables farmers to produce the same output using less area. However, the influential idea of the Jevons Paradox suggests that technological innovations will increase deforestation as more productive farmers demand more land.

This paper provide evidence that technical change in agriculture was associated with environmental benefits in the Brazilian agricultural frontier. Exploring changes in production possibilities coming from technological innovations that adapted soybeans to the agro-climatic characteristics from Central Brazil, we find that technological innovations were not associated with increases in agriculture along the extensive margin. We find significant changes in the intensive margin with increases in cropland and native forests and decreases in native pastures. These changes indicate that total land use decreased as a consequence of the technological innovations. Therefore, this episode of technical change generated environmental benefits as it reduced deforestation.

These findings are consistent with farmers being capital constrained and crop cultivation being capital-intensive. Adjustments in input use evidence that crop cultivation is indeed more intensive in modern inputs and capital than cattle ranching and that resource constraints might be binding and preventing expansion in the extensive margin. This particular land use adjustment to the technological innovations reflected characteristics of the Brazilian agricultural frontier in the period. Farmers operated in an environment with limited access to credit, inadequate infrastructure, and insecure land rights. However, the paper highlights the importance of considering substitution possibilities across crops and resource constraints to understand the effect of technological innovations in agriculture on deforestation. Therefore, it provides an important contribution to the debate on the effects of technical change on deforestation.

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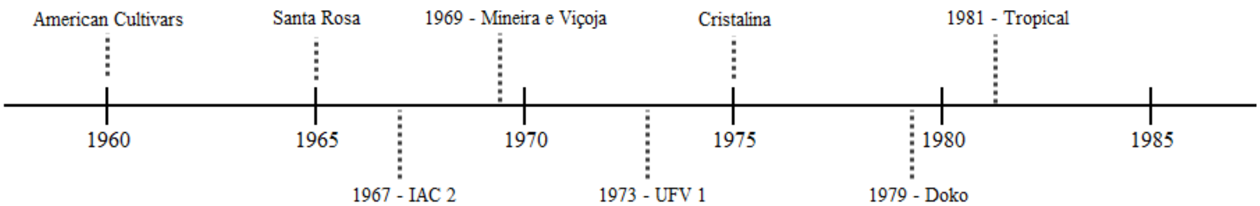
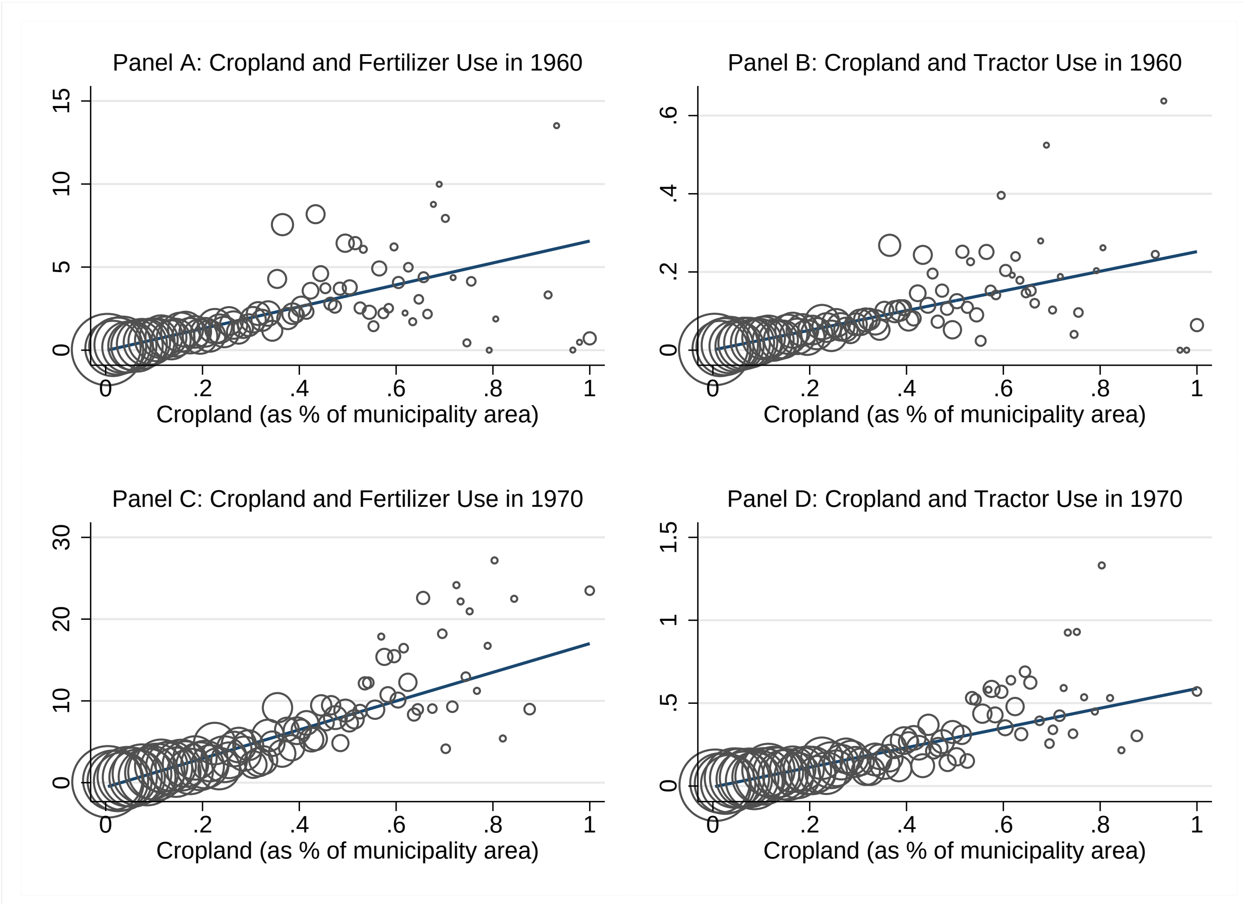
Figure 1: The Evolution of Soybean Varieties available in Central Brazil



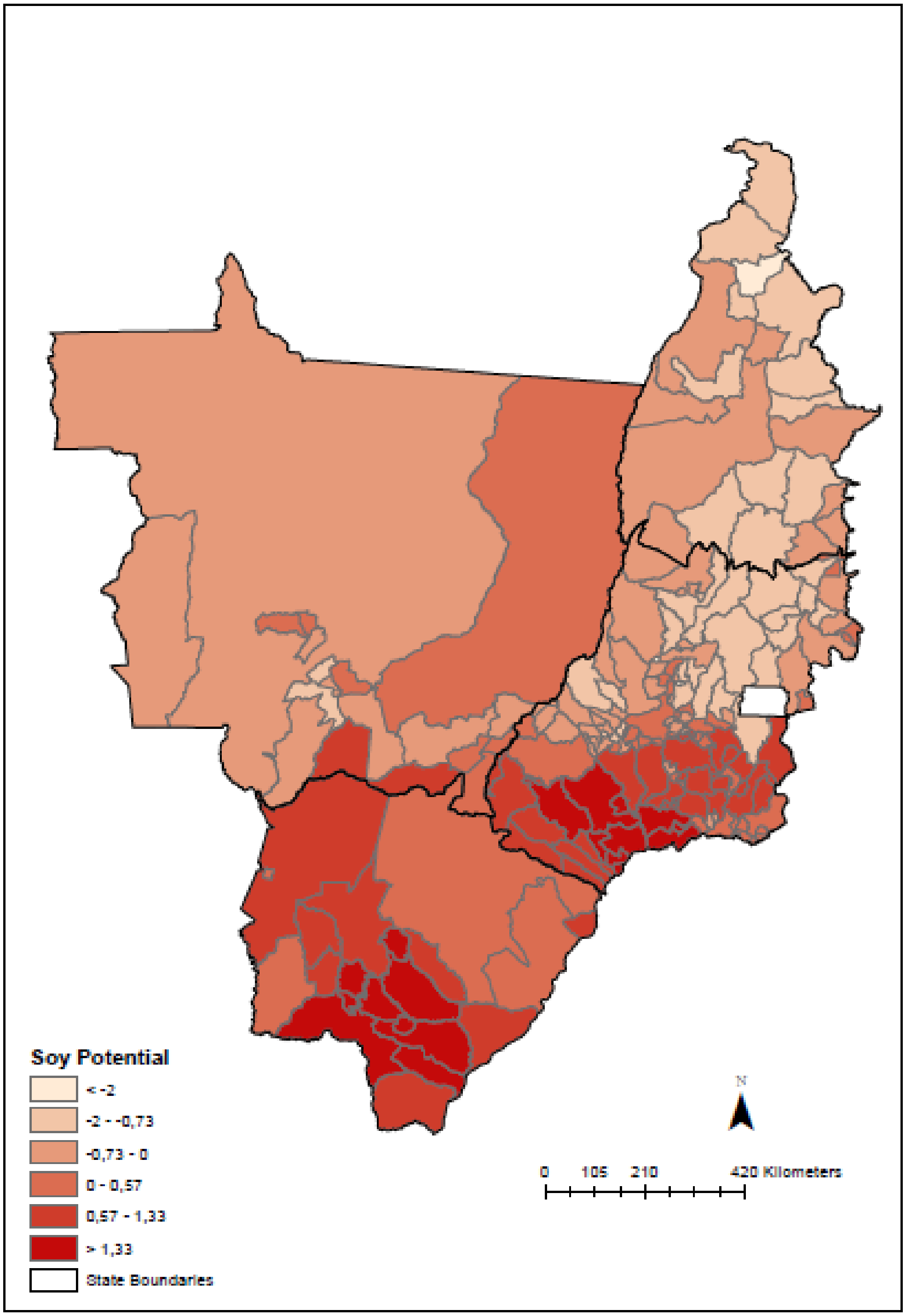
Notes: Own compilation from several historical sources.

Figure 2: Cropland and Input Use in the Brazilian Agriculture



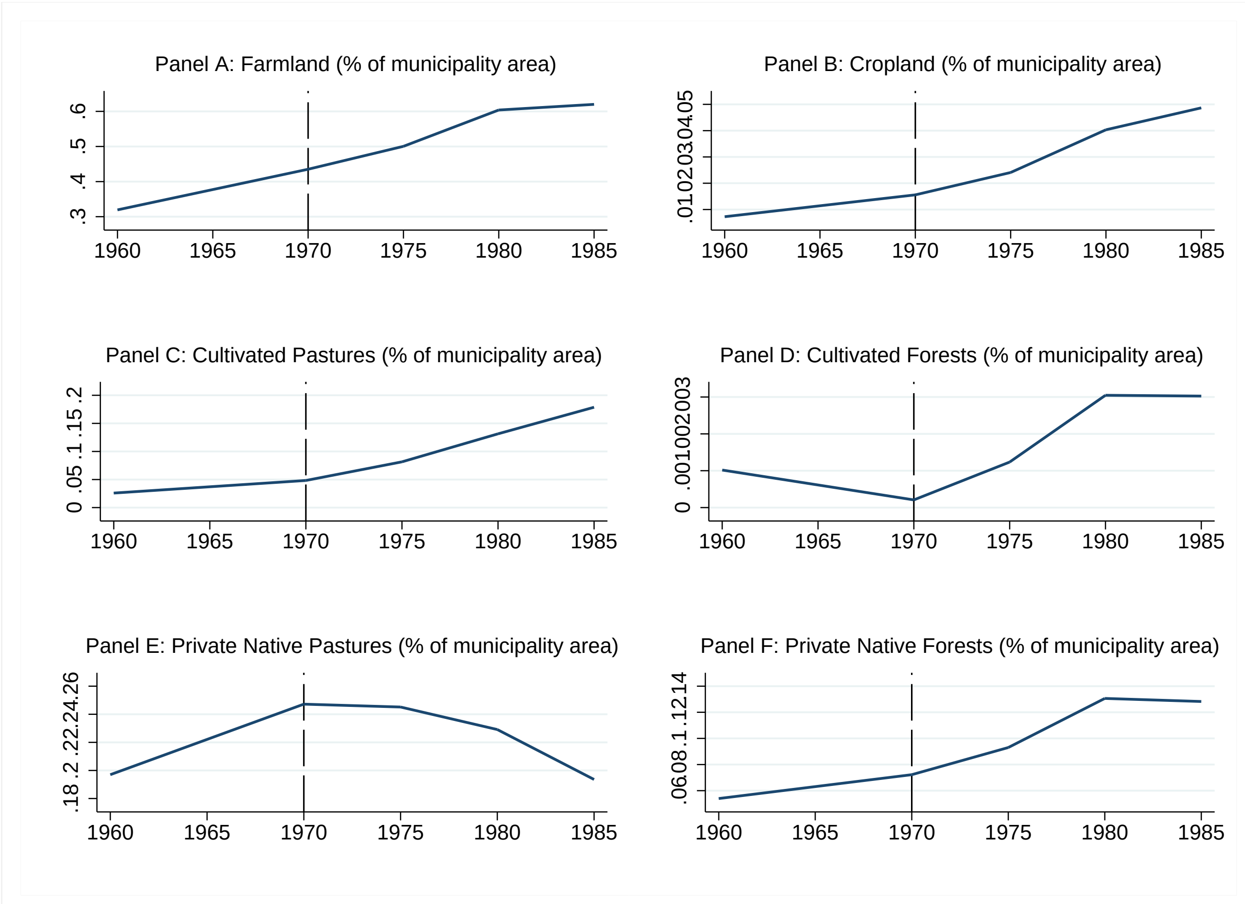
Notes: Each panel plots the bivariate relationship between the share of cropland and an input use measure in the Brazilian Agriculture. Fertilizer Use is defined as expenditures with fertilizers per 100 municipality hectares. Tractor Use is defined as the number of tractors per 100 municipality hectares. Data is aggregated at one percentage point bins. Each panel plots the fit from a bivariate regression of the input use measure on cropland and the underlying data. The size of the hollow circles is proportional to the number of observations in each bin.

Figure 3: Soybean Potential across Central Brazil



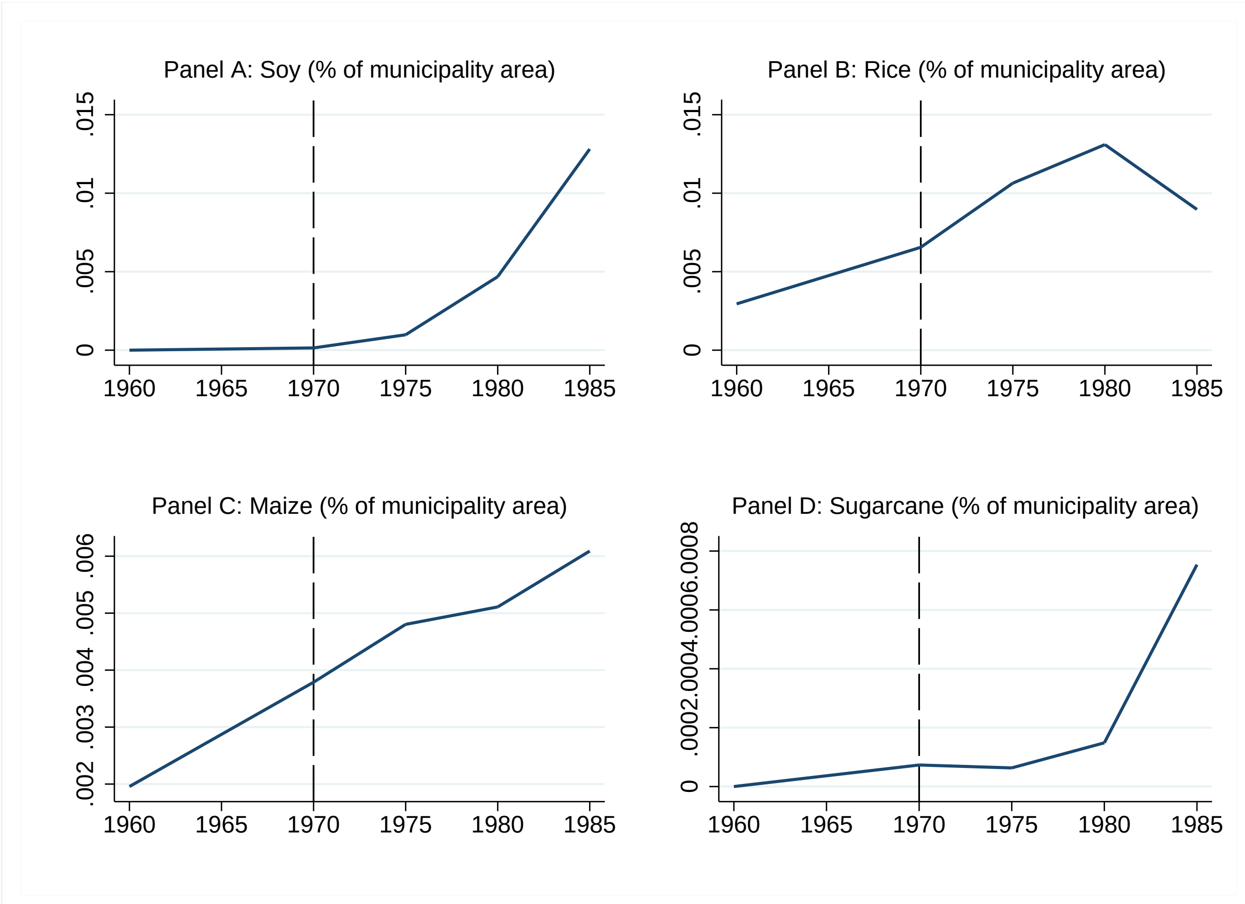
Notes: Data from the FAO/GAEZ database. The map presents the value of the soybean potential measure for each of the sample 193 municipalities. The map was constructed combining the contemporaneous municipalities map with information from the Minimum Comparable areas from the Brazilian Institute of Economic Research (IPEA).

Figure 4: Aggregate Changes in Land Use in Central Brazil



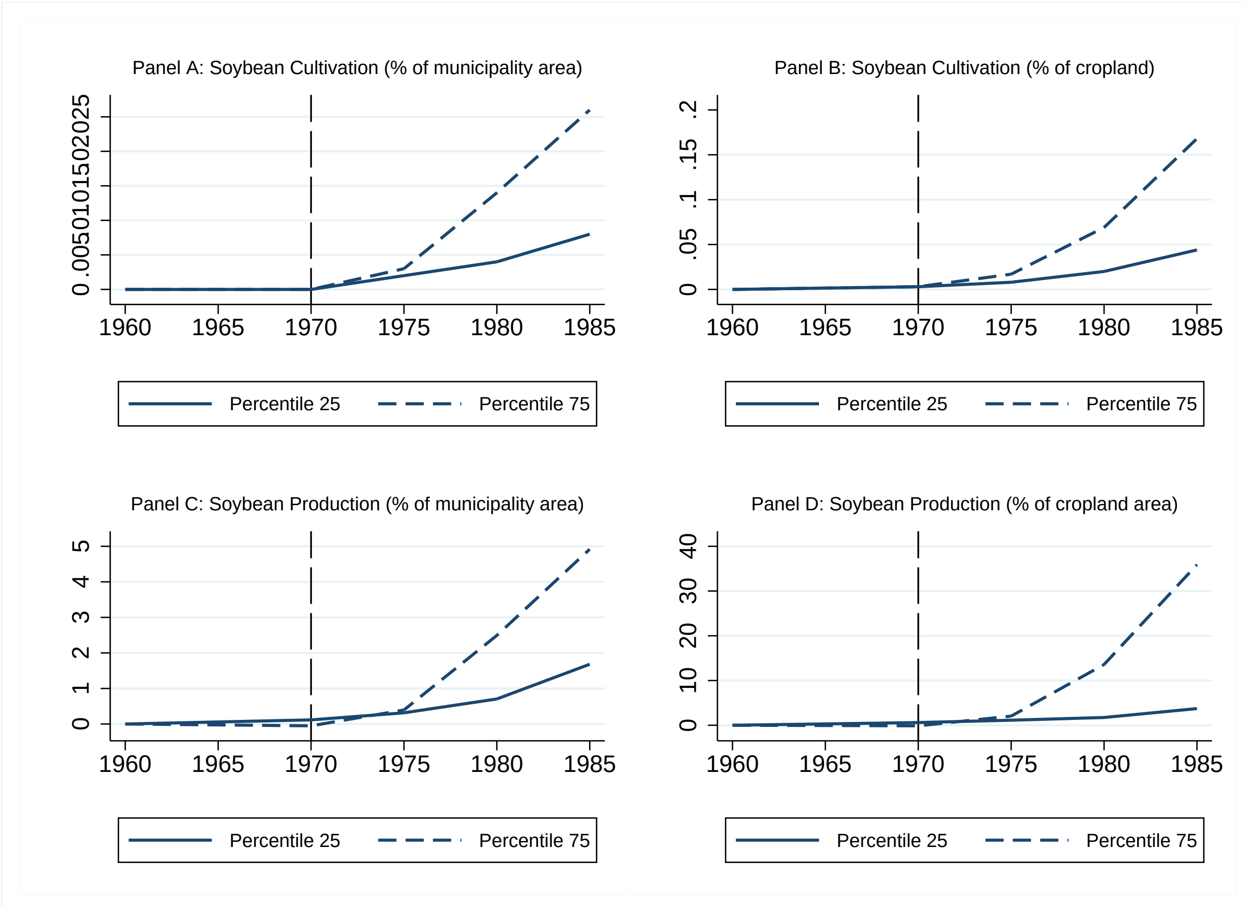
Notes: Each panel reports weighted averages over the period for the 193 municipalities in the sample weighted by municipality area. All variables are reports as share of the municipality area. Panel A reports the share of farmland. Panel B reports the share of cropland. Panel C reports the share of cultivated pastures. Panel D reports the share of cultivated forests. Panel E reports the share of native pastures. Panel F reports the share of native forests. Panels E and F refer to native vegetation in the existing farmland.

Figure 5: Aggregate Changes in Crop Cultivation in Central Brazil



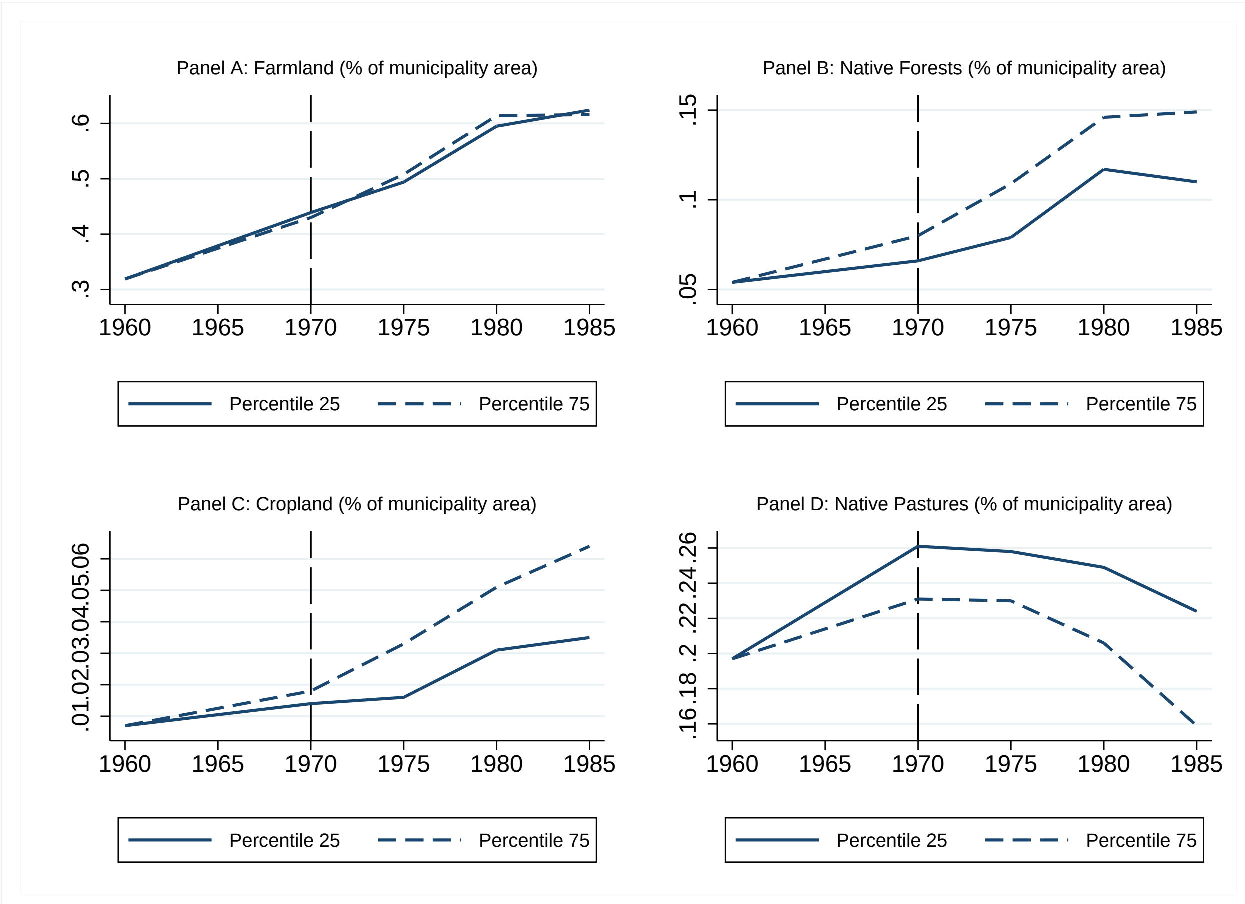
Notes: Each panel reports weighted averages over the period for the 193 municipalities in the sample weighted by municipality area. All variables are reports as share of the municipality area. Panel A reports the share of soybean cultivation Panel B reports the share of rice cultivation. Panel C reports the share of maize cultivation. Panel D reports the share of sugarcane cultivation.

Figure 6: Simulated Changes in Soybean Cultivation and Production



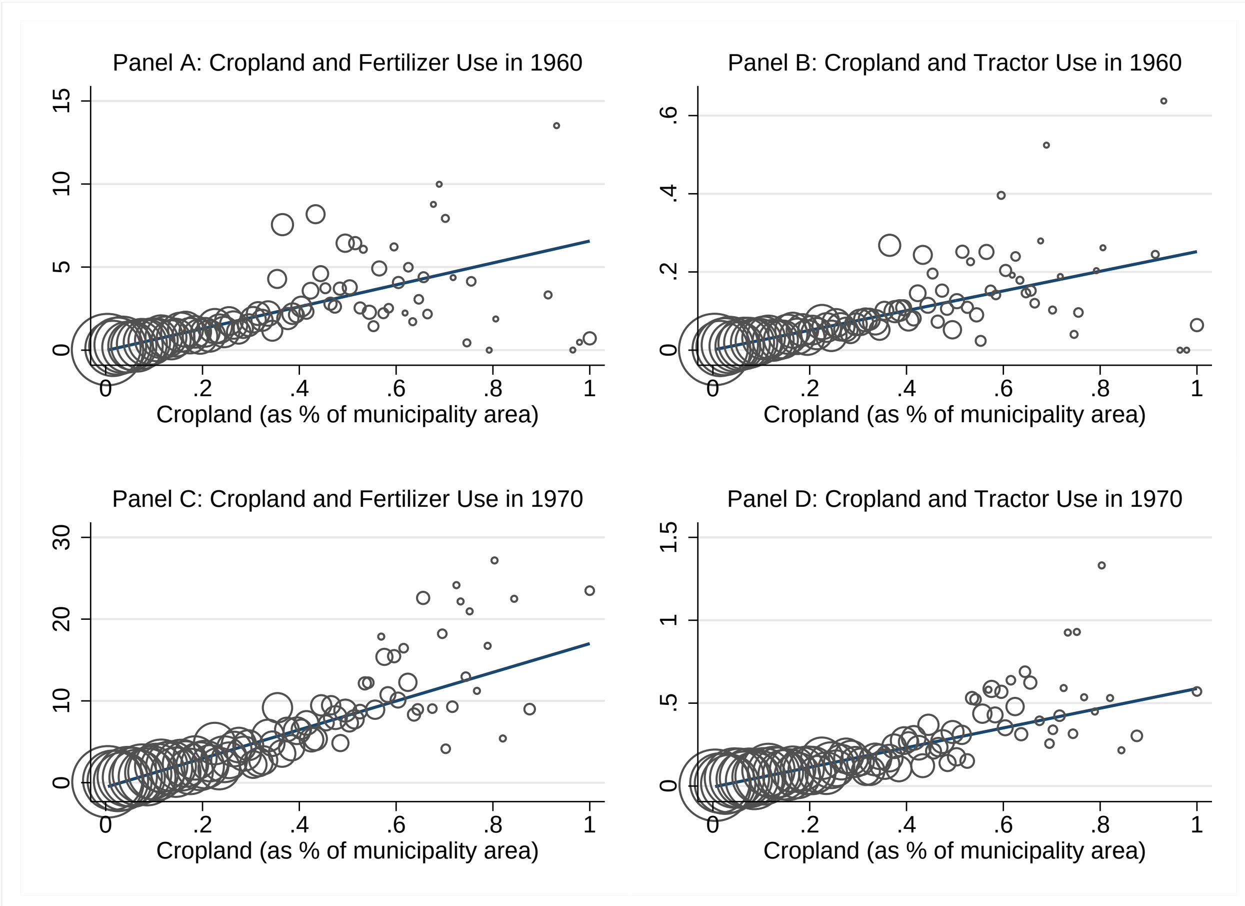
Notes: The figure simulates the change in soybean cultivation and production in a municipality in the 75th percentile of the soybean potential distribution compared to a municipality in the 25th percentile of this distribution. The outcome variables are indicated in the panel title. In each panel, the estimated change in the land use variable is computed estimating equation (5) in text. To simulate the change in soybean cultivation and production, all variables expect the soybean potential are evaluated at their mean. Soybean potential is evaluated in the 25th percentile of the soybean potential distribution in the solid lines and in 75th percentile of the soybean potential distribution in the dashed lines.

Figure 7: Simulated Changes in Land Use



Notes: The figure simulates the change in land use in a municipality in the 75th percentile of the soybean potential distribution compared to a municipality in the 25th percentile of this distribution. The outcome variables are indicated in the panel title. In each panel, the estimated change in the land use variable is computed estimating equation (5) in text. To simulate the change in land use, all variables expect the soybean potential are evaluated at their mean. Soybean potential is evaluated in the 25th percentile of the soybean potential distribution in the solid lines and in 75th percentile of the soybean potential distribution in the dashed lines.

Figure 8: Simulated Changes in Input Use



Notes: The figure simulates the change in input use in a municipality in the 75th percentile of the soybean potential distribution compared to a municipality in the 25th percentile of this distribution. The outcome variables are indicated in the panel title. In each panel, the estimated change in the input use variable is computed estimating equation (5) in text. To simulate the change in input use, all variables expect the soybean potential are evaluated at their mean. Soybean potential is evaluated in the 25th percentile of the soybean potential distribution in the solid lines and in 75th percentile of the soybean potential distribution in the dashed lines.

Table 1: Changes in Area and Yields for the Main Agricultural Products

	Rice	Beans	Maize	Soybeans	Cattle Grazing
	(1)	(2)	(3)	(4)	(5)
Panel A: 1960-1970 percentage change					
Area	122.20%	72.35%	93.58%		32.58%
Yield	-21.46%	-39.27%	-16.60%		12.99%
Panel B: 1970-1985 percentage change					
Area	36.85%	10.87%	60.77%	8886.20%	25.97%
Yield	11.00%	39.52%	46.70%	140.40%	56.72%

Notes: The table computes the aggregate changes in area (hectares) and yield (tons/hectare) for the main agricultural products from Central Brazil in the periods 1960 to 1970 (*Panel A*) and 1970 to 1985 (*Panel B*).

Table 2: Municipal Characteristics by Soybean Suitability using Modern Technologies

		Coefficient on Soybean Suitability		
	Mean	No Controls	Within-State	Controls
	(1)	(2)	(3)	(4)
Panel A: Land Use				
Share of Farmland	0.319	0.154***	0.112***	0.024
	(0.082)	(0.037)	(0.023)	(0.025)
Share of Cropland	0.007	0.004**	0.006**	0.003
	(0.002)	(0.002)	(0.003)	(0.003)
Share of Native Pastures	0.197	0.116***	0.072***	0.030
	(0.053)	(0.028)	(0.018)	(0.020)
Share of Cultivated Pastures	0.026	0.023***	0.028***	0.012**
	(0.008)	(0.005)	(0.005)	(0.006)
Share of Native Forests	0.054	0.006	-0.003	-0.019**
	(0.012)	(0.007)	(0.007)	(0.008)
Share of Cultivated Forests	0.001	-0.000	-0.001	-0.002
	(0.000)	(0.001)	(0.001)	(0.001)
Panel B: Production				
Rice Production per 100 hectares	0.368	0.283**	0.505**	0.356
	(0.116)	(0.129)	(0.225)	(0.218)
Maize Production per 100 hectares	0.244	0.161**	0.219**	0.124
	(0.074)	(0.065)	(0.098)	(0.102)
Sugarcane Production per 100 hectares	0.126	-0.030	-0.073	-0.188
	(0.042)	(0.035)	(0.059)	(0.139)
Number of Cattle per 100 hectares	5.754	3.661***	2.876***	0.954
	(1.666)	(0.835)	(0.787)	(1.746)
Panel C: Input Use				
Tractors per 100 hectares	0.001	0.002***	0.004***	0.003***
	(0.000)	(0.001)	(0.001)	(0.001)
Value of Capital per 100 hectares	5.061	4.103***	3.624***	2.099
	(1.516)	(0.760)	(0.816)	(1.391)
Exp. w/ Fert. per 100 hectares	0.007	0.008***	0.010***	0.005*
	(0.002)	(0.003)	(0.003)	(0.003)
Liming Use (% of farms)	0.001	0.000	-0.000	0.000
	(0.000)	(0.001)	(0.001)	(0.001)
Panel D: Land Value				
Farm Value per 100 hectares	12.638	4.103***	3.624***	2.099
	(3.751)	(0.760)	(0.816)	(1.391)
Farmland Value per 100 hectares	7.577	7.908***	9.134***	6.384***
	(2.274)	(1.260)	(1.840)	(1.924)
Number of Municipalities	193	193	193	193

Notes: Column 1 reports averages weighted by municipality area. Column 2 through 5 report coefficients from regressing each outcome on soybean potential. Column 2 reports unconditional estimates. Column 3 adds state fixed effects. Column 4 adds quadratic functions of latitude and longitude and distance to Brasília and to the coast. All regressions are weighted by municipality area. Robust standard errors are reported in parenthesis. *** p<0.01 ** p<0.05 * p<0.10

Table 3: Estimated Changes in Soybean Adoption, by Soybean Potential using Modern Technologies

	Relative Change after 1960			
	Cultivation (% of mun. area)	Cultivation (% of cropland area)	Production (per 100 mun. hectares)	Production (per 100 cropland hectares)
	(1)	(2)	(3)	(4)
Soybean Potential x 1970	-0.000	-0.000	-0.073	-0.490
	(0.001)	(0.006)	(0.216)	(1.100)
Soybean Potential x 1975	0.001	0.007	0.115	0.401
	(0.001)	(0.008)	(0.207)	(1.299)
Soybean Potential x 1980	0.008**	0.037	1.355**	6.036
	(0.003)	(0.023)	(0.579)	(3.883)
Soybean Potential x 1985	0.014***	0.099**	2.625***	18.190**
	(0.005)	(0.041)	(1.005)	(8.171)
Municipality Fixed Effects	Yes	Yes	Yes	Yes
State x Year Fixed Effects	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
R-Squared	0.752	0.857	0.729	0.840
Number of Municipalities	193	193	193	193
Number of Observations	965	965	965	965

Notes: The table reports estimates from equation 5 in the text. The dependent variables are reported on the top of the respective columns. Controls are the following variables: average farm size, number of farms per 100 municipality hectares, the number of private and state-owned bank branches per 100 municipality hectares and the interaction between year dummies and baseline population density, latitude (quadratic function), longitude (quadratic function), the distance to Brasília (quadratic function), the distance to the coast (quadratic function) as well as the baseline values of all variables in Panels A through D in Table 2. Regressions are weighted for total municipality area and standard errors are clustered at the municipality level are reported in parentheses. *** p<0.01 ** p<0.05 * p<0.10

Table 4: Estimated Changes in Land Use, by Soybean Potential using Modern Technologies

	Relative Change after 1960					
	Total Farmland	Native Forests	Cropland	Native Pastures	Cultivated Forests	Cultivated Pastures
	(1)	(2)	(3)	(4)	(5)	(6)
Soybean Suitability x 1970	-0.005	0.011	0.002	-0.022	0.000	0.014
	(0.020)	(0.007)	(0.003)	(0.018)	(0.000)	(0.009)
Soybean Suitability x 1975	0.011	0.023*	0.012***	-0.023	-0.001	0.016
	(0.027)	(0.012)	(0.005)	(0.023)	(0.001)	(0.012)
Soybean Suitability x 1980	0.014	0.021*	0.015**	-0.032	0.000	0.023
	(0.026)	(0.011)	(0.006)	(0.026)	(0.002)	(0.016)
Soybean Suitability x 1985	-0.006	0.029***	0.022***	-0.050**	-0.000	0.014
	(0.023)	(0.008)	(0.007)	(0.020)	(0.002)	(0.019)
Municipality Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
State x Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
R-Squared	0.975	0.900	0.921	0.946	0.804	0.929
Number of Municipalities	193	193	193	193	193	193
Number of Observations	965	965	965	965	965	965

Notes: The table reports estimates from equation 5 in the text. The dependent variables are reported on the top of the respective columns. Controls are the following variables: average farm size, number of farms per 100 municipality hectares, the number of private and state-owned bank branches per 100 municipality hectares and the interaction between year dummies and baseline population density, latitude (quadratic function), longitude (quadratic function), the distance to Brasília (quadratic function), the distance to the coast (quadratic function) as well as the baseline values of all variables in Panels A through D in Table 2. Regressions are weighted for total municipality area and standard errors are clustered at the municipality level are reported in parentheses. *** p<0.01 ** p<0.05 * p<0.10

Table 5: Estimated Changes in Input Use, by Soybean Potential using Modern Technologies

	Relative Change after 1960			
	Tractors (per 100 mun. hectares)	Value of Capital (per 100 mun. hectares)	Expend. w/ Fertilizers (per 100 mun. hectares)	Liming Use (% of farms)
	(1)	(2)	(3)	(4)
Soybean Potential x 1970	0.002	1.175	0.005	0.000
	(0.002)	(1.560)	(0.097)	(0.001)
Soybean Potential x 1975	0.008***	1.383	0.276*	0.002
	(0.003)	(2.101)	(0.159)	(0.002)
Soybean Potential x 1980	0.016***	4.188	1.075***	0.026***
	(0.005)	(4.779)	(0.330)	(0.007)
Soybean Potential x 1985	0.025***	12.809**	1.419***	0.028***
	(0.006)	(6.481)	(0.410)	(0.008)
Municipality Fixed Effects	Yes	Yes	Yes	Yes
State x Year Fixed Effects	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
R-Squared	0.936	0.950	0.847	0.828
Number of Municipalities	193	193	193	193
Number of Observations	965	965	965	965

Notes: The table reports estimates from equation 5 in the text. The dependent variables are reported on the top of the respective columns. Controls are the following variables: average farm size, number of farms per 100 municipality hectares, the number of private and state-owned bank branches per 100 municipality hectares and the interaction between year dummies and baseline population density, latitude (quadratic function), longitude (quadratic function), the distance to Brasília (quadratic function), the distance to the coast (quadratic function) as well as the baseline values of all variables in Panels A through D in Table 2. Regressions are weighted for total municipality area and standard errors are clustered at the municipality level are reported in parentheses. *** p<0.01 ** p<0.05 * p<0.10

Table 6: Estimated Changes in Other Products' Production, by Soybean Potential using Modern Technologies

	Relative Change after 1960			
	Number of Cattle (per 100 mun. hectares)	Maize Production (per 100 mun. hectares)	Rice Production (per 100 mun. hectares)	Sugarcane Production (per 100 mun. hectares)
	(1)	(2)	(3)	(4)
Soybean Potential x 1970	1.235	0.097	0.133	0.009
	(0.853)	(0.098)	(0.146)	(0.467)
Soybean Potential x 1975	0.756	0.377	0.447*	-0.100
	(0.884)	(0.302)	(0.227)	(0.518)
Soybean Potential x 1980	2.114	0.567*	0.355*	0.407
	(1.319)	(0.335)	(0.194)	(1.035)
Soybean Potential x 1985	1.688	1.002**	0.146	2.158
	(1.707)	(0.503)	(0.148)	(3.754)
Municipality Fixed Effects	Yes	Yes	Yes	Yes
State x Year Fixed Effects	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
R-Squared	0.967	0.886	0.878	0.619
Number of Municipalities	193	193	193	193
Number of Observations	965	965	965	965

Notes: The table reports estimates from equation 5 in the text. The dependent variables are reported on the top of the respective columns. Controls are the following variables: average farm size, number of farms per 100 municipality hectares, the number of private and state-owned bank branches per 100 municipality hectares and the interaction between year dummies and baseline population density, latitude (quadratic function), longitude (quadratic function), the distance to Brasília (quadratic function), the distance to the coast (quadratic function) as well as the baseline values of all variables in Panels A through D in Table 2. Regressions are weighted for total municipality area and standard errors are clustered at the municipality level are reported in parentheses. *** p<0.01 ** p<0.05 * p<0.10

Table 7: Estimated Changes in Farm Values, by Soybean Potential using Modern Technologies

	Relative Change after 1960			
	Value per 100 municipality hectares			
	Farm	Land	Farm	Land
	(1)	(2)	(1)	(2)
Soybean Potential x 1970	3.002	1.656	-2.302	-2.350
	(5.615)	(4.004)	(3.806)	(2.602)
Soybean Potential x 1975	12.964	11.404	-3.467	-1.423
	(9.169)	(7.062)	(7.850)	(5.870)
Soybean Potential x 1980	39.990**	39.162***	10.499	15.207
	(17.803)	(14.953)	(12.924)	(10.744)
Soybean Potential x 1985	40.782*	27.237*	-5.896	-10.225
	(21.159)	(15.616)	(18.161)	(13.017)
Municipality Fixed Effects	Yes	Yes	Yes	Yes
State x Year Fixed Effects	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Number of Tractors and Expend. w/ Fertilizers	No	Yes	No	Yes
R-Squared	0.966	0.963	0.976	0.975
Number of Municipalities	193	193	193	193
Number of Observations	965	965	965	965

Notes: The table reports estimates from equation 5 in the text. The dependent variables are reported on the top of the respective columns. Controls are the following variables: average farm size, number of farms per 100 municipality hectares, the number of private and state-owned bank branches per 100 municipality hectares and the interaction between year dummies and baseline population density, latitude (quadratic function), longitude (quadratic function), the distance to Brasília (quadratic function), the distance to the coast (quadratic function) as well as the baseline values of all variables in Panels A through D in Table 2. Regressions are weighted for total municipality area and standard errors are clustered at the municipality level are reported in parentheses. *** p<0.01 ** p<0.05 * p<0.10

Table 8: Estimated Changes in Agricultural Outcomes using Placebo Measure of Agricultural Potential

	Relative Change after 1960				
	Farmland	Cropland	Native Pastures	Tractors (per 100 mun. hectares)	Liming Use (% of farms)
	(1)	(2)	(3)	(4)	(5)
Soybean Potential (Low Input) x 1970	0.007	-0.009**	0.024	-0.008**	-0.000
	(0.021)	(0.004)	(0.018)	(0.003)	(0.002)
Soybean Potential (Low Input) x 1975	0.027	-0.009*	0.033*	-0.008**	0.001
	(0.027)	(0.005)	(0.019)	(0.004)	(0.003)
Soybean Potential (Low Input) x 1980	0.029	-0.006	0.007	-0.005	-0.005
	(0.025)	(0.006)	(0.021)	(0.006)	(0.008)
Soybean Potential (Low Input) x 1985	0.031	-0.011	-0.003	-0.010	-0.009
	(0.024)	(0.008)	(0.018)	(0.007)	(0.008)
Municipality Fixed Effects	Yes	Yes	Yes	Yes	Yes
State x Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes
R-Squared	0.975	0.918	0.945	0.932	0.812
Number of Municipalities	193	193	193	193	193
Number of Observations	965	965	965	965	965

Notes: The table reports estimates from equation 5 in the text. The dependent variables are reported on the top of the respective columns. Controls are the following variables: average farm size, number of farms per 100 municipality hectares, the number of private and state-owned bank branches per 100 municipality hectares and the interaction between year dummies and baseline population density, latitude (quadratic function), longitude (quadratic function), the distance to Brasília (quadratic function), the distance to the coast (quadratic function) as well as the baseline values of all variables in Panels A through D in Table 2. Regressions are weighted for total municipality area and standard errors are clustered at the municipality level are reported in parentheses. *** p<0.01 ** p<0.05 * p<0.10

A Appendix

A.1 Model Solution

The farmer's problem is:

$$\max_{T_C, T_p} \Pi(T_P, T_C), \; s.t \; \kappa_P T_P + \kappa_C T_C \leq K \tag{A.1}$$

in which $\Pi(T_P, T_C) = A_P F(T_P) + A_C F(T_C) - \kappa_P T_P - \kappa_C T_C$ as presented in the main text.

Land use in equilibrium (T_P^*, T_C^* and T_F^*) can be computed solving equation (A.1). There are two relevant cases: when the farmer is unconstrained and when farmer is constrained. We consider the effects of technological innovations on land use in both cases.

Case 1: Unconstrained Farmer ($\kappa_P T_P + \kappa_C T_C < K$)

In this case, the constraint in equation (A.1) is redundant. The farmer simply chooses T_P and T_C in order to maximize $\Pi(T_P, T_C)$. The farmer's problem is separable in this situation and cropland and pasture choices are independent. The independence can be easily seen in the first order conditions below:

$$\frac{A_P}{\kappa_P} \frac{\partial F(T_P^*)}{\partial T_P} = 1 \tag{A.2}$$

$$\frac{A_C}{\kappa_C} \frac{\partial F(T_C^*)}{\partial T_C} = 1 \tag{A.3}$$

The intuition behind equations (A.2) and (A.3) is straightforward: the farmer equalizes the marginal benefit of cropland and pastures ($\partial F(T_P^*)/\partial T_P^*$and $\partial F(T_C^*)/\partial T_C^*$) to their respective marginal costs (κ_P / A_P and κ_C / A_C). We can compute the impact of an increase in A_C on T_P^* and T_C^* applying the implicit function theorem to equations (A.2)-(A.3) above:

$$\frac{dT_P^*}{dA_C} = 0 \tag{A.4}$$

$$\frac{dT_C^*}{dA_C} = -\frac{\kappa_C}{A_C^2}\left(\frac{\partial^2 F(T_C^*)}{\partial T_C^2}\right)^{-1} > 0 \tag{A.5}$$

Differentiating T_F^* with respect to A_C, we also obtain:

$$\frac{dT_F^*}{dA_C} = -\frac{dT_P^*}{dA_C} - \frac{dT_C^*}{dA_C} < 0 \tag{A.6}$$

Equations (A.4)-(A.6) represent the effects of the technological innovations that adapted soybeans to Central Brazil on land use when farmers are unconstrained. As discussed in the main text, farmers expand cropland without reducing pastures in this case. As a consequence, the area with native forests decreases and the technological innovations are associated with negative environmental externalities as in the Jevons Paradox.

Case 2: Constrained Farmer ($\kappa_P T_P + \kappa_C T_C = K$)

In this case, the constraint in equation (A.1) is binding. Therefore, the farmer's problem is not separable and crop cultivation and cattle grazing choices are connected. We can write $T_P = (K - \kappa_C T_C)/\kappa_P$, substitute in the profit function and solve for T_C. The first order condition is:

$$\frac{A_C}{\kappa_C}\frac{\partial F(T_C^*)}{\partial T_C} = \frac{A_P}{\kappa_P}\frac{\partial F(T_P^*)}{\partial T_P} \geq 1 \tag{A.7}$$

The intuition behind equation (A.7) is straightforward: the farmer equalizes the marginal benefit of cropland to the marginal benefit of pastures. One the one hand, in the unconstrained case, the benefit from cropland must compensate its costs. On the other hand, in the constrained case, the benefit from cropland must also compensate the net loss from the reduction in pasture area it generates.[17]

We can compute the impact of an increase in A_C on T_C^* applying the implicit function theorem to equation (A.7):

$$\frac{dT_C^*}{dA_C} = -\frac{\left(\partial F(T_C^*)/\partial T_C\right)(1/\kappa_C)}{(A_C/\kappa_C)\left(\partial^2 F(T_C^*)/\partial T_C^2\right) + (A_P/\kappa_P)(\kappa_C/\kappa_P)\left(\partial^2 F(T_P^*)/\partial T_P^2\right)} > 0 \tag{A.8}$$

[17] Notice that the right-hand term is equal or greater than one as T_P^* is equal or greater in the unconstrained case than in the constrained case.

Differentiating T_P^* and T_F^* with respect to A_C, we obtain:

$$\frac{dT_P^*}{dA_C} = -\frac{\kappa_C}{\kappa_P}\frac{dT_C^*}{dA_C} < 0 \tag{A.9}$$

$$\frac{dT_F^*}{dA_C} = -\frac{dT_P^*}{dA_C} - \frac{dT_C^*}{dA_C} = \left(\frac{\kappa_C}{\kappa_P} - 1\right)\frac{dT_C^*}{dA_C} > 0 \tag{A.10}$$

The result in equation (A.10) is a direct consequence of the assumption that crop cultivation is more capital-intensive than cattle grazing ($\kappa_C > \kappa_P$). Equations (A.8)-(A.10) represent the effects of the technological innovations that adapted soybeans to central Brazil on land use when farmers are constrained. As discussed in the main text, farmers expand cropland reducing pastures in this case. The reduction in pastures is larger than the increase in cropland due to the differences in capital use in these activities. As a consequence, the area with native forests decreases and the technological innovations are associated with positive environmental externalities.

Combining the results in (A.4)-(A.6) and (A.8)-(A.10), we obtain the results in the equations (2)-(4) in the main text. Notice that the condition for farmers to be constrained or not can be derived from equations (A.2) and (A.3). Solving these equations for T_P^* and T_C^*, we obtain the following expressions:

$$T_P^* = \left(\frac{\partial F}{\partial T_P}\right)^{-1}\left(\frac{\kappa_P}{A_P}\right) \tag{A.11}$$

$$T_C^* = \left(\frac{\partial F}{\partial T_C}\right)^{-1}\left(\frac{\kappa_C}{A_C}\right) \tag{A.12}$$

Define $\overline{K}$ as the "desired" capital demand of a farmer. Using the resource constraint and equations (A.11) and (A.12), we can write it as:

$$\overline{K} = \kappa_P\left(\frac{\partial F}{\partial T_P}\right)^{-1}\left(\frac{\kappa_P}{A_P}\right) + \kappa_C\left(\frac{\partial F}{\partial T_C}\right)^{-1}\left(\frac{\kappa_C}{A_C}\right) \tag{A.13}$$

The farmer is unconstrained when $\overline{K} < K$ and constrained when $\overline{K} \geqslant K$. In the former case, the "desired" capital demand is smaller than the available capital, while it is equal or larger than the available capital in the latter case.

A.2 Data Sources

The data used in this paper comes from several sources. We describe below the definition of all variables used in the analysis.

Geographic Characteristics. All geographic characteristics are constructed using GIS software. We combine municipality maps and lists of the municipalities composing each Minimum Comparable Area (MCA) to build a map of municipalities consistent with the 1960 administrative division and borders. We then combine this map with raster data from the FAO/GAEZ database to measure soybean potential - main variable of interest in the paper. This variable is defined as the difference between Potential Soybean Yields under the High and Low Input regimes. Other geographic variables - area, latitude, longitude, distance to the coast and distance to *Brasília* - are built directly using the municipalities map.

Land Use. All land use variables are constructed combining information from the Agricultural Census with information on municipality area. The share of *farmland* is the ratio between total farmland and the municipality area. The shares of *cropland*, *native pastures*, *cultivated pastures*, *native forests* and *cultivated forests* are the ratio between in of these land use categories and the municipality area.

Agricultural Production. Rice, maize, sugarcane and soybean production are measured as the product's output (in tons) per each 100 hectares of municipality area. Cattle production is proxied using the number of cattle per each 100 hectares of municipality area. These variables are constructed combining information from the Agricultural Census with information on municipality area.

Input Use. Tractor use is measured as the number of tractors per each 100 hectares of municipality area. Capital use is measured as the value of farm capital (buildings, machines and vehicles) per each 100 hectares of municipality area. Fertilizer Use is measures as the total expenditures with fertilizers and pesticides per each 100 hectares of municipality area. Liming use is measures as the share of farms which uses liming. The value of farm capital and the expenditures with fertilizers and pesticides are deflated to 2012 using Corseuil and Foguel (2002)'s method. These variables are built using information from the Agricultural Census.

Land Values. Land values are constructed using two different variables: total farm value and total farmland values. Both variables are expresses per each 100 municipality hectares and are deflated to 2012 using the same method described above. Again these variables' construction uses data from the Agricultural Census.

Baseline Controls. Baseline controls are measured in 1960 and are drawn from several sources. Population is measured using data from the Population Census and bank branches is measured using data from the Central Bank. Both variables are normalized using municipal area and expressed per each 100 municipality hectares. The number of farms, average farm size and access to electricity are measured using data from the Agricultural Census. Number of farms is the total number of rural establishments per 100 municipality hectares. Average farmsize is the ratio between total farmland and the number of farms. Access to electricity is the share of farms with electric power.