# Technological Diffusion and Bundled Contracts: Soy Boom in Brazil

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**Abstract**

Bundled contracts are a promising mechanism for the diffusion of capital-intensive technologies in developing regions. The introduction of a new type of farmer–trader contract, which bundles soy price guarantees, credit, technical assistance, and a technological package, has enabled rapid economic growth in Brazil's soy industry. This paper investigates the role of this bundled contract on the diffusion of soy technologies and the resulting effect on the productivity of the agricultural sector in Brazil. To guide my empirical analysis, I model farmers' technological and contracting choices, focusing on the benefits of bundling in removing multiple barriers to the adoption of capital-intensive technologies in low-income regions such as the Brazilian Savanna. To model farmers' contracting and technological choices, I combine farm-level data for 1.5 million commercial farms from the 1996 and 2006 Brazilian agricultural census surveys, capturing the fastest period of soy expansion in Brazil. I present empirical evidence that contracting accelerates the diffusion of soy technology and increases the supply elasticity of soy in Brazil. I estimate that the introduction of bundled contracts explains 84% of total soy expansion in the agricultural frontier of the Brazilian Savanna.

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# 1. Introduction

Economic institutions such as credit markets, property rights, and contracts are fundamental determinants of economic growth. These institutions define the incentives for private investments in new production technologies, which lead to higher productivity and income (Acemoglu, Johnson, and Robinson, 2005). Developing countries could therefore greatly benefit from an understanding of how successful cases of institutional innovation in low-income regions stimulate technological diffusion. The potential of technological change to spur economic development has led social scientists to study the adoption process of a large range of technologies in many sectors (Foster and Rosenzweig, 2010; Feder and Umali, 1993; Feder, Just, and Zilberman, 1985) and to model the theoretical interaction between institutions and technological progress (Acemoglu, 2007; Acemoglu, Johnson, and Robinson, 2005). However, empirical analysis of institutional innovation in developing countries is challenging for several reasons: (1) the gradual nature of institutional change; (2) the lack of micro data combining institutional change, technological change, and economic outcomes; and (3) the large capital requirements necessary to change production technologies, limiting the application of randomized experiments. The main contribution of this paper is to provide empirical evidence of the effect of a new contracting institution in the agricultural sector of a developing country.

The Brazilian soy boom represents a well-suited case for the examination of the benefits of a novel farmer-trader contract on agricultural productivity, presenting a unique opportunity to contrast the diffusion of distinct soy technologies. To the best of my knowledge, this analysis of the Brazilian soy boom is the first empirical study of the introduction of a new type of bundled contract, which includes technology and technical assistance, in the adoption of new advanced production systems in a developing country. In 1994, the Brazilian government introduced market reforms that transitioned Brazil's agriculture from a government-managed to a market-oriented sector. The drastic improvements enabled by the market reforms can be seen in Figure 1, which shows how these reforms influenced the diffusion processes of two distinct soy technologies, each implemented in different regions of Brazil. *The Economist* refers to the soy boom in Brazil as "The Miracle of the Cerrado," highlighting the increase in the value of crop production from 23 to 108 billion Reals (R$2010) (from 13 to 62 billion USD), from 1996 to

2006. Crop production value increased by 370% compared with a 30% increase in GDP during the same period.

Before the market reforms, the Brazilian government promoted soy expansion in the Savanna with the introduction of a new soy technology designed for low fertility soil, biological-nitrogen-fixing soy (BNF), and with direct financing of soy production. After the market reforms, a group of large international organizations, known in Brazil as the ABCD group (Archer Daniels Midland, Bunge, Cargill, and Louis Dreyfus), expanded their investments in the country using a vertical-integration business strategy through investments in fertilizer and soy processing companies. The ABCD group introduced a new type of contract that bundled soy price guarantees, credit, and a technological package with seeds, inputs, and pesticides (Junior, 2011; Silva, 2012). This market-oriented expansion in the Savanna can be seen in Figure 1 in the much steeper diffusion function of the dashed line.

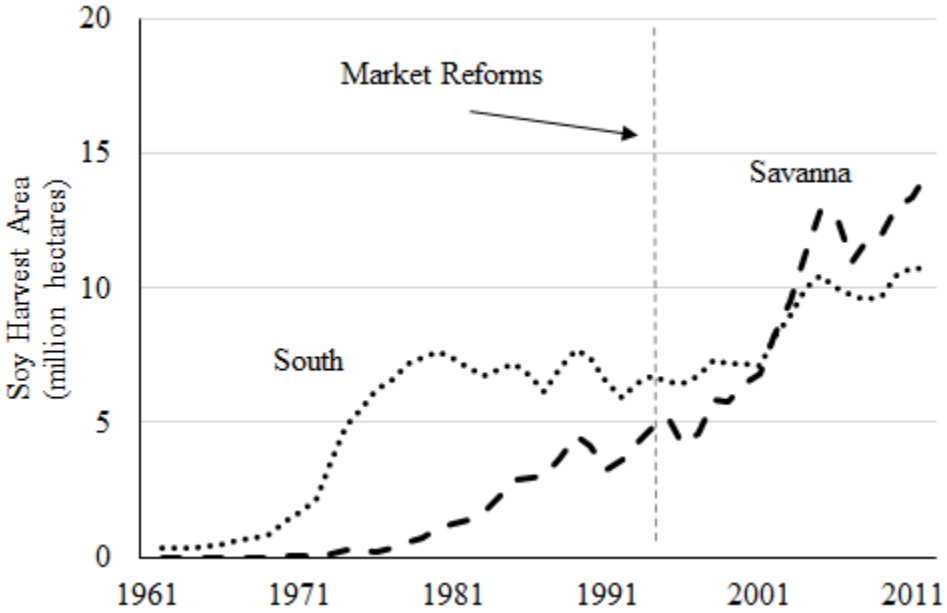


Figure 1. Soy Expansion in two regions of Brazil, before and after market reforms (vertical dashed line).

To assess further the applicability of the new farmer-trader contract, I contrast the simultaneous diffusion of two soy technologies, BNF and genetically modified soybeans (GM), in distinct regions of Brazil. Figure 1 additionally shows the diffusion process of soy production in the south of Brazil (dotted line), a developed region of the country with soil and climate characteristics more suitable to soy production. Soy first expanded in the south in the early 1970s as a complementary crop to subsidized wheat. After the market reforms, in 2001, the Brazilian government approved the commercialization of GM soy. The diffusion of GM soy in the south is illustrated in Figure 1 by an S-shaped curve that spans from year 2000 to 2007.

Measuring the effect of institutional innovations is very challenging, in part because of the lack of data. Economists rarely have access to farm level data on the private contracting choices of farmers, or even on the technological choices of farmers across a large geographical region. In order to study the effect of a new type of contract on agricultural productivity, it is necessary to combine data on farmers' contracting and technology choices with the resulting agricultural and environmental outcomes. The closest source of information at this level in Brazil is the Agricultural Census produced by the Brazilian Institute of Geography and Statistics (IBGE, 1996; IBGE, 2006). In this analysis, I combined farm level data for 1.5 million commercial farms from two Brazilian Agricultural census surveys, years 1996 and 2006, which spans the fastest period of soy expansion in Brazil. Access to confidential farm-level census data in Brazil, which contains information on farmer land use, production system, type of seed and industrial integration, is highly restricted and this is the first analysis of Brazil that combines farm-level data from two agricultural census surveys. The combination of the two census surveys is essential to detect farmers' choices of contracting and technology, to identify technological change and contracting effects, as well as to control for pre-existing trends in agricultural outcomes and potential confounding factors such as opportunity cost of land and historical land use.

In order to guide my empirical analysis, I investigate how different technologies, characterized by the factor-bias of technological change and the magnitude of conversion costs, affect the profitability of contracting. A vertically integrated trading company has better access to credit, input, and output markets, and can therefore offer the farmer a cost-effective bundled contract in exchange for a share of soy production profits. From the farmer's perspective, the profitability of

contacting will then depend on the complexity of the technology and on the farmer's own cost function. The farmer's benefit of contracting tends to increase with more complex and capital intensive technologies, such as the BNF soy, in particular in frontier regions where the conversion cost is higher and technical assistance becomes more valuable. In contrast, the profitability of contracting tends to decrease with a technology designed for high productivity land, with low conversion costs, such as labor-saving GM soy. The key theoretical implication is that the combination of capital-biased technological change with contracting can accelerate technological diffusion and have a "multiplier effect" on agricultural expansion, agricultural productivity, and on the price elasticity of agricultural supply.

To identify the effect of the new farmer-trader contract on agriculture development, we need a source of exogenous variation on the propensity to adopt the new contract. I exploit the fact that the potential profitability of adopting the new contract-technology bundle changes with exogenous variation in land suitability to soy production. Development economists have often used suitability measures to identify technological change effects on agricultural and development outcomes (Foster and Rosenzweig, 2010; Bustos, Caprettini, and Ponticelli, 2016). In this analysis, I adapt this identification approach to estimate the effects of the bundled contract-technology package. I explore how exogenous variation in soil characteristics lead to the adoption of different production technologies, which then affect the profitability of contracting.

I use two types of suitability measures that are determined exogenously from Brazilian farmer's actual production choices. First, I obtain variation in soil characteristics such as pH level and nitrogen content that differentiates the suitability of soil to BNF and GM production (Embrapa, 2014). Secondly, I use estimates of soy potential yield from the Food and Agriculture Organization (FAO)'s Global Agro-Ecological Zones (GAEZ) database (FAO/IIASA, 2014) (Bustos, Caprettini, and Ponticelli, 2016). The GAEZ estimates predict soy yield under different levels of input use. The difference between potential yields under different levels of input capture the marginal value of agricultural intensification. I found that these suitability metrics are strong predictors of the adoption of different technologies.

Once contracting choice is defined using the micro census data and proper measures of soy suitability are constructed, identifying contracting effects is still very challenging. While

technological change can increase the profitability of contracting, so can variation in the price of soy and in the opportunity cost of land, which act as confounding factors. I use a panel dataset with price data at the Municipality level to measure changes in expected prices. I explore the large variation in distance from producer locations to markets and ports in Brazil, in combination with changes in a state policy that significantly increased the local price of soy, to identify price effects on soy expansion. Local agricultural prices in developing countries can vary significantly because of differences in distance to market and poor transportation infrastructure. The Brazilian savanna is a good example of a productive agriculture frontier located over 1,000 km from main ports and the large consumer markets along the Brazilian coast. Finally, I take advantage of the rich census dataset to test robustness of contracting effects using different sets of controls and fixed effects, and different subsamples of farmers based on land-use before and after the introduction of the new contract.

I find that the introduction of the new type of contract bundling prices, technology, and technical assistance accelerated the diffusion of BNF soy in the Savanna region of Brazil, which includes two of the poorest states of the country, Piaui and Maranhao. The bundling contract was an effective technological diffusion mechanism in the Brazilian Savanna because it addressed simultaneously several constrains that are typical of developing regions: access to credit markets, to output markets, to advanced technologies, to cost-reducing economies of scale, and to qualified technical assistance. I summarize my quantitative estimates of contracting effects in terms of two types of outcomes: agricultural expansion and productivity, and price responsiveness of agricultural supply.

Contracting explained 84% of soy expansion in the Savanna frontier, where there was no soy production before the introduction of bundled contract. In locations where soy was produced before the introduction of the contract, contracting explained 37% of soy expansion. Contracting increased total value of agricultural output by 200% in the frontier and 65 % in producing locations. During the same period GDP increased by 30%. Contracting also increased the probability of adoption of complementary technologies. I find that in the Savanna frontier contracting increased the probability of introducing a multiple crop soy-corn production system by 50%. One important implication of the contract-driven agricultural expansion is the intensification of agricultural production in the frontier through use of advanced technologies

and through introduction of multiple crop systems. According to census data, average soy yield in the Savanna was slightly higher than yields in the South.

A novel finding of this work is that contracting helps explain the large heterogeneity in the long-run supply elasticity of soy in Brazil. I find a large heterogeneity in long-run price elasticity of soy expansion, consistent with results from Hausman (Hausman, 2012). I find average price elasticities of 1.1 for Brazil, 1.3 for the Southern region, and 3.5 for the Savanna. Most of this variance in the supply elasticity is explained by the indirect effect of pricing on the adoption of the new bundled contract. In the Savanna, the price elasticity ranged from 2.3 in locations with low probability of contracting to 5.4 in locations with high probability of contracting. These results imply that institutional and technological changes might have a much larger effect than price-driven policies designed for promoting agricultural development or for mitigating negative environmental outcomes of land-use change such as deforestation.

**Related Literature.** This analysis most closely relates to the economic literature investigating institutional constraints to technological adoption in developing countries (Acemoglu, Johnson, and Robinson, 2005; Foster and Rosenzweig, 2010; Feder and Umali, 1993; Feder, Just and Zilberman, 1985). In particular, there are several theoretical studies that examine the role of interlinkage contracts in addressing credit market failures in developing countries (Gangopadhyay and Sengupta, 1987; Bell, 1988) and model the relationship between contracting and technological change (Acemoglu, 2007). Acemoglu shows that contract incompleteness leads to underinvestment in advanced technologies and the degree of underinvestment varies with the characteristics of the technology (Acemoglu, 2007).

Few studies investigate the bundling effect of contracts on technological adoption. One example is the randomized field experiment of Gine and Yang in Malawi (Gine and Yang, 2008). Gine and Yang test take-up of alternative contracts for adoption of hybrid groundnut seeds, one simple loan contract versus a contract that bundles loans and insurance. They found a significantly higher take-up for the simple loan contract and argue that the loan contracts were cheaper and already contained implicit insurance guarantees. The innovative experiment of Gine and Yang suggests that bundling mechanisms can be very influential in the farmer adoption decision. Randomized field experiments are unfortunately not feasible for analyzing the effect of the

introduction of more complex bundling mechanisms on the adoption of capital intensive production systems.

My empirical approach combines the model for estimating technological change effects used by Bustos, Caprettini, and Ponticelli (2016), and Braganca, Assuncao, and Ferraz (2014), with the econometric estimation of price elasticity of soy expansion used by Hausman (Hausman, 2012). Bustos, Caprettini, and Ponticelli (2016), and Braganca, Assuncao, and Ferraz (2014) use aggregated data to estimate the effects of soy technological change in agricultural and development outcomes in Brazil, using cross-sectional variation in soil suitability measures. Both papers do not account explicitly for price changes. Hausman uses a panel of aggregated data for prices and acreage to estimate long-run price elasticities of soy expansion in Brazil and finds large spatial heterogeneity in price responses. Hausman models technological change using different functional forms for time trends. My empirical analysis builds on these three papers by modeling both technological change and price changes using micro level data.

A major challenge in studying institutional innovation is detecting the institutional change using non-experimental datasets. Conley and Udry investigated the effect of social learning, an institutional mechanism for technological change, in the adoption of Pineapple in Ghanna (Conley and Udry, 2012). Learning networks are not easily observed in typical datasets, so Conley and Udry collected detailed data about individual relations to define information networks that allowed them to estimate the effect of social learning on technological adoption. The definition of the institution, social networks in this case, can therefore have a substantial influence on results. In my analysis, I use the farm-level agricultural census data to construct alternative definitions of contracting based on farm integration to industry, existence of private debt and private technical assistance, and adoption of a technological package consistent to observed contracts. I use these different definitions of contracting to test the robustness of my results. Conley and Udry found robust evidence that farmers adopted successful practices from their information network. The importance of learning effects demonstrated in Conley and Udry's paper reinforces the value of a bundling mechanism for technological diffusion that simultaneously addresses multiple barriers to adoption.

The next section summarizes the institutional context underlying the soy boom in Brazil. I focus on the key aspects of the market reforms implemented in Brazil in the mid-nineties, and in the

definitions of the technological change and the new farmer-trader contract. In Section 3, I develop a simple theoretical framework that characterizes the technological change and the farmer decision process. I present the key theoretical implications and preview my empirical approach. In Section 4, I describe the three main datasets and provide summary descriptive statistics on the key variables used in the empirical analysis. Section 5 presents quantitative results for the farmer's choice of contracting and the effect of contracting on agricultural expansion, on agricultural productivity, and on the price responsiveness of soy expansion. Section 6 concludes with a summary of the main findings of my work and the broader implications of technological diffusion and contracting in developing countries.

## 2. Soy Boom in Brazil

The area harvested with soy in Brazil grew rapidly from 400 thousand to 20 million hectares in just 50 years, further exemplified by a large average compound growth rate over 8% per year. Even more surprising than the expansion was the distribution of growth in these five decades. It took 40 years, from the mid-1960s to the mid-1990s, to reach the first 10 million hectares harvested, an area the size of Kentucky, but only an additional 10 years to double the harvested area to 20 million hectares. Figure 2A shows the soy boom in Brazil measured in harvested area and highlights the 10-year period from 1996 to 2006 that includes the fastest period of soy expansion in Brazil, which is the focus of this analysis. In this section, I summarize the institutional context behind this expansionary period, focusing on the roles of market reforms, technological change, and contracts on soy expansion.

### Market Reforms and Price Changes

The 1980s in Brazil are known as the "lost decade" because of the long economic crisis with annual inflation rates ranging from 65% to 1,782% (Sachs, 1999) (Figure 2F). In the mid-1990s, the Brazilian government implemented a series of market reforms that stabilized the economy, controlled inflation, and reduced government debt. The most important reform was "Plano Real" in 1994, a set of macroeconomic measures that included the creation of a new currency (the Real), budget cuts, high interest rates, tight controls on exchange rates, and reductions in import tariffs. Plano Real and subsequent policy changes had a large effect on the agricultural sector. In

this section, I summarize the importance of these market reforms on soy expansion in terms of their effects on three prices: interest rates, soy prices, and input prices.

Figure 2B shows annual government expenditure in agriculture credit (BCE, 2016). Agricultural expansion in the 1970s was driven in large part by government financing; however, with the fiscal crisis of the 1980s, government financing declined sharply, reaching its historical lowest point of about 23 billion Reals in 1996. At that point, many farmers were highly indebted and had defaulted on their loans, to the point that the government had to renegotiate farmers' loans (Silvestrini and Lima, 2012). Moreover, controlling inflation required the Brazilian government to raise real interest rates. The average annual real interest rate in Brazil from 1994 to 1998 was 20.2%, reaching 30% in 1999 (Melo, 1999). As a result, agricultural credit provided by the government as well as by private financial institutions became severely constrained.

In contrast to the constraining effects on credit, the market reforms of soy prices and input prices were beneficial to farmers. The Brazilian government reduced tariffs on imports to spur competition and increase productivity. Between 1989 and 1994, the index of agricultural input prices, which includes purchases of fertilizers and new farming equipment, decreased by about 25% in real terms (Melo, 1999). Even more significantly, two policy changes in Brazil raised the price farmers received for exporting soy by over 50% during the 10-year period between 1996 and 2006, despite relatively constant international prices. The most critical policy change was the approval of the Kandir Law in 1996 (Kume and Piani, 1997 ; Soares, 2012); this law eliminated the state tax on the circulation of products and transport services (ICMS) related to the export of primary goods, an effective tax cut of about 20%. ICMS is the main state tax in Brazil and it varies across states and transportation routes. Figure 2C shows the evolution of the average ICMS rate as applied to soy exports. The Kandir Law also changed the relative prices of raw and processed soy, favoring exports of raw soy, and therefore reducing investments in building new processing capacity in Brazil (Junior, 2012).

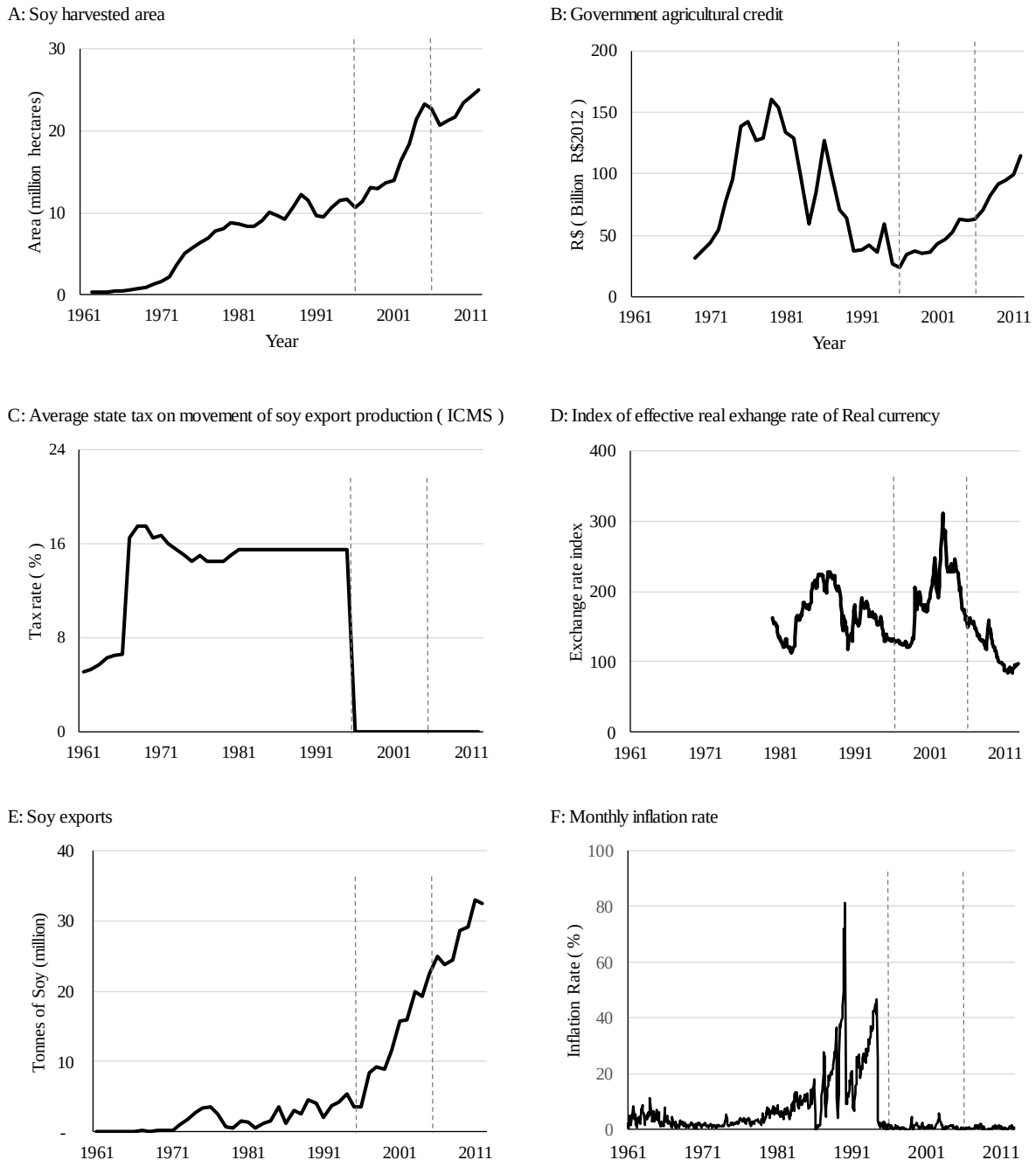


Figure 2. Soy boom in Brazil: institutional context

Notes: Figures A and D: data from CONAB and IPEA. Figures B and F: data from the Central Bank of Brazil. Figure C: data based on Rezende (Rezende, 2012). Index in Figure D equals 100 in 2010. Figure E: data from FAO.

The Kandir Law, which had the effect of a “fiscal devaluation”, was created in part to compensate for the appreciation of the Real after the implementation of Plano Real (Kume and Piani, 1997). Figure 2D shows the evolution of the effective real exchange rate of the Real. In 1994, the Brazilian government pegged the Real to the Dollar to control inflation, but the peg system proved too expensive and had to be removed in January 1999, resulting in a 66% devaluation. In summary, the combination of the Kandir Law tax cut and change in exchange rate policy represented a very large price incentive for soy farmers which led to a dramatic increase in soy exports, as illustrated in Figured 2E. By 2006, Brazil was the second largest soy exporter in the world, behind the United States, with total soy export revenue of about US$ 5.6 billion (FAO, 2016).

**Technological Change**

The case of soybean expansion in Brazil is unique because of the role of technological change in adapting a temperate crop for production in the warmer and drier climate of the savanna. Figure 1 breaks down soy expansion in the two main production regions in Brazil, the South and the Savanna regions. The South region has a temperate climate and the highest Human Development Index of Brazil. The Savanna, also called the Cerrado, represents 21% of Brazil’s landmass; the tropical climate and acidic soil in this region of Brazil was considered to be unsuitable for farming prior to the 1960s. The Savanna extends to latitudes as low as 5 degrees, reaching the poorest states in Brazil. While soy expansion began in the South, from the 1980s, the majority of harvested area growth occurred in the Savanna, leading it to surpass the South in total soy-harvested area by 2002. Figure 1 illustrates the evolution of regional soy expansion.

The technological innovation that enabled soy production in the Savanna was the development of soy seeds for low latitudes using biological nitrogen fixation (BNF). This process converts atmospheric nitrogen in plants through the inoculation of seeds with specific types of bacteria, such as Bradyrhizobium in the case of soy (Hungria, Campos, and Mendes, 2001). In the 1960s, when the government was heavily involved in developing the soy industry, the Brazilian government sponsored a plant-breeding program that combined enhanced seeds with nitrogen-fixing bacteria strains (Alves, Boddey, and Urquiaga, 2002). The seed-bacteria combination was developed specifically for poor nutrient soils such as Savanna soils without fertilizer application, and this led to new soybean varieties self-sufficient in nitrogen (Alves, Boddey, and Urquiaga,

2002). In 1996, Dobereiner estimated that BNF technology enabled Brazil to save up to US$3.2 billion (1996 USD) per year on nitrogen fertilizer for soy production, which was critical for production in the Savanna due to the overall high cost of farming in this region.

To enable soy production in the Savanna, it was essential to implement BNF technology and ensure Savanna soil had the proper chemical composition for agricultural production. Approximately 46% of the Brazilian Savanna landmass has a type of soil known as Latossolos, which is naturally low in fertility (Campos et al., 2003). Savanna soils, including Latossolos, are acidic, with a high content of aluminum, and deficient in most nutrients, lacking therefore the proper chemical properties for farming. On the positive side, these soils have good physical properties that make them suitable for mechanized farming; hence, if the soil chemistry could be adjusted, a large proportion of the Brazilian Savanna could be converted into productive crop production. However, clearing the land and chemically correcting the soil can be expensive; large quantities of lime and fertilizers are necessary to prepare the soil, and depending on the previous use of land, the clearing process necessary for mechanized farming (destoca) can be very costly. Resende (2003) reported a conversion cost of $600 per hectare in 2003, three times the cost of the land at the time, with over half of the cost, $340, stemming from lime and fertilizers. *The Economist* (2010) reported that 25 million tons of lime were used in 2003, about 5 tons per hectare[2]. The high capital investment in "producing the soil" in the Savanna makes BNF soy technology capital-intensive.

Finally, another important technology introduced between 1996 and 2006 was genetically modified (GM) soy. GM technology, which has been applied to multiple crops, has been well studied by researchers in multiple fields (Qaim, and Zilberman, 2003; Ainsworth et al., 2012). In 1996, Monsanto introduced the first commercial GM soy designed to resist high doses of pesticide applications, simplifying weed control and reducing labor costs through a reduced frequency of pesticide applications. The GM soybean diffused rapidly in Brazil despite a long legal dispute between farmers and environmental organizations. In 2006, about 3.6 million hectares of GM soy were harvested in Brazil (IBGE, 2006).

[2] In my interviews with farmers, I heard reports of up to 15 tons of lime being necessary for soil conversion in the first three years.

## Contracts

The Brazilian government was initially heavily involved in the soy industry through the development of new technologies and financing of production; however, after the fiscal crises and implementation of market reforms, the industry transitioned to a market-oriented model with the expansion of the role of international trading corporations. Starting in the mid-1990s, four trading companies, known as the ABCD group, Archer Daniels Midland, Bunge, Cargill, and Louis Dreyfus, expanded their investments in the Brazilian soy market through a series of acquisitions of fertilizer and soy-processing companies (Junior, 2011; Silva, 2012). These trading companies followed a consistent strategy of the vertical integration of the soy supply chain, through investments in the production and commercialization of fertilizers, and direct financing of farmers through anticipated sales contracts. The goal of the trading companies was to guarantee the supply of soy at the required quality levels in order to meet their own demands for processing and export contracts. To establish long-term relationships with producers, the ABCD group offered farmers a package of services that included financing, price guarantees, technical assistance, and inputs for production (Junior, 2011; Souza, 2007). By 2005, 67% of Brazilian soy production was financed by trading companies, and by 2007, Bunge and Cargill, through their partnerships and acquisitions, controlled 57.4% of the fertilizer market (Junior, 2011).

The trader-farmer contract is an agreement made before planting starts, committing the farmer to supply a specific quantity of soy, at harvest, for a fixed price, in exchange for inputs and financial resources to cover production costs. This agreement includes technical assistance and a "technological package" formed by seeds, fertilizers, and pesticides. Although this agreement can be applied to any technology, historically most contracts have involved the implementation of BNF soy. The technical assistance service also involves monitoring the production and timing of the harvest to ensure compliance. In practice, the farmer commits a number of 60 kg bags of soy to the trader and receives the resources and inputs to start planting. In 2005, for example, a ton of fertilizer for soy production was worth 19.6 bags of soy (Prince, 2011). These types of contracts are also known in Brazil as "green soy" (soja verde) in reference to the timing of negotiation. The technological package represents a "recipe" for soy production with inputs provided, and in many cases produced, by the trading companies. A benefit of the farmer-trader contract for the farmer is the ability to quickly make adjustments during the season (Embrapa,

2016). For example, if the farmer had unexpected production problems after planting, s/he could contact the trading group's technical assistance for help with technological choices and input supplies. On the other hand, a concern regarding the technological package is whether the input list supplied by the trader represents the best long-run production technology for the farm. For a manufacturer of inputs, packaging can be an effective marketing strategy. For example, Monsanto introduced GM soy as a package that included new pesticide-resistant GM seeds and pesticides (Farina and Zylbersztajn, 1996).

The three main components of the farmer-trader agreement, namely a fixed sales price, anticipated resources in the form of cash or inputs, and a technological package of inputs, remain the same independently of the form and channel of intermediation among the economic agents involved. In this analysis, I use the most general definition for the contract, as described above, which is consistent with the trading companies' strategies. Nevertheless, there are variations of contracts depending on the negotiation power of each agent (Silva, 2011; Resende and Zylbersztajn, 2008). In some cases, a contract can be signed directly between a farmer and the input manufacturer, in the form of an input-output exchange. Alternatively, the farmer can sign a contract with a trader to fix sales prices and enter into another agreement with a manufacturer for the technological package of inputs. Finally, a farmer has the option to apply for traditional government financing directly through government agencies or cooperatives (Silva, 2011), a strategy employed increasingly since 1996, as seen in Figure 2E. In 2010, 69.8% of the area planted with soy in the South and 32.4% in the Midwest, a region in the Savanna biome, was financed by government credit (Silva, 2011).

## 3. Optimal Choice of Technology and Contracting

In order to guide my empirical analysis, in this section I model the farmer's joint choice of technology and contracting. A risk-neutral farmer planning production for plot of land $i$ before the start of the season makes a joint decision about land-use, $j$, technology, $A$, and contracting, $I$. The optimal choice of technology and contracting is described by the optimization problem:

$$\{ A^*, I^* \}_i = \underset{A,I}{\operatorname{argmax}}\, \Pi_i \, ( A, I, P, X, Z) \tag{1}$$

$\Pi_i$ is the net revenue expected from producing crop $j$ on plot $i$, subject to a vector of output and input prices $P$ and a set of farm and plot characteristics $Z$. I omit the crop subscript to simplify notation, as this analysis concerns only soy. The farmer's net revenue function is then:

$$\Pi_i(A) = P\,F(X, K, A) - W\,X(A) - (1 + r)\,K(A) - CC(A) \tag{2}$$

where $F(X, K, A)$ is the farmer production function, depending on inputs, $X$, capital, $K$, and technology, $A$. $W$ and $r$ are, respectively, the price of inputs and the interest rate. $CC$ captures the cost of converting land to technology $A$, including learning costs. Note that all terms of the net revenue function depend on the production technology. The optimal technology $A$ for any plot will depend on the soil and climate characteristics of the land, Z, such that $A = A(Z)$. To simplify notation, I will just refer to technology as $A$.

The key concept of the new farmer-trader contract is to bundle prices, technology, and technological assistance. The main objective of the trading company is to secure a large supply of soy at competitive prices. Industrial processing of soy adds low value, so the cost of raw soy drives the profitability of trading and processing companies. The bundling strategy allows the trading company to address several barriers to soy production in developing regions. Trading companies have access to international credit and output markets, access which reduces their cost of capital and transaction costs related to market access. Also, through vertical integration, the trading company can reduce the costs of procuring inputs and tailor a cheaper technological package to its own internal supply chain. Finally, by adding technical assistance, the trading company reduces the conversion cost of adopting its technological package, monitors soy production, and locks farmers into a long-term relationship.

The new farmer-trader contract can be represented by the set:

$$I = \{\, P', W', r', A' \,\} \tag{3}$$

where the prime superscript differentiates the set of prices and technology bundled in the contract. From the farmer's perspective, the profitability of contracting can be represented by:

$$\Delta\Pi_i(A) = \Pi_i'(A', P', W', r') - \Pi_i(A, P, W, r) \tag{4}$$

The farmer's choice of contracting will depend on the characteristics of the technology and the structure of the soy market. The standard model of interlinkage contracts (i.e., those that link

markets, in this case credit and output markets) in the development economics literature assumes fixed technology and no competition between traders, focusing only on credit market failure (Gangopaphiay and Sengupta, 1987). These assumptions hold for subsistence agriculture sectors in India and Africa; however, commercial farming in Brazil features evident competition among traders, which allows farmers to retain a larger share of profits. Although credit-market constraints do play a central role in the expansion of soy production in Brazil, bundled contracts have other sources of efficiency, including lower input costs resulting from traders' vertical-integration strategy and lower transaction costs for accessing output markets. In this analysis, I abstract away distributional aspects of contracting, that is, I assume a competitive market structure, in order to focus on the linkage between technology and contract profitability.

**Factor-biased Technological Change**

In this section, I differentiate two technologies, BNF and GM soy, relevant to the expansion of soy production in Brazil, based on the factor-bias of technological change, following the approach of Acemoglu (2002) and Bustos, Caprettini, and Ponticelli (2016). I then derive empirical implications for the choice of technology and contracting from their economic characterization.

Consider a CES production function $F(T, K, A)$ with two inputs: land, $T$, and working capital, $K$. For simplicity, I include conversion costs, $CC$, and production inputs, $X$, in a broad definition of working capital $K$, since I do not study substitution effects among these different types of production inputs. Then, define technology as the index $A = (A_{K,} A_T)$, where $A_K$ and $A_T$ are the technology terms in the CES production function:

$$F = [\gamma (A_K K)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(A_T T)^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} \tag{5}$$

In this function, $A_K$ is capital-augmenting technical change and $A_T$ is land-augmenting technical change. $\gamma$ is a weighting parameter for the factors of production, and $\sigma$ is the elasticity of substitution between land and working capital. Variations in technical change are then represented by changes in $A = (A_{K,} A_T)$. The bias of technical change depends on how improvements in technology affect the marginal products of factors of production (Acemoglu,

2002). Differentiating the marginal product of capital, $F_K$, with respect to land-augmenting technical change, $A_T$, gives:

$$\frac{\partial F_K}{\partial A_T} = \frac{\Gamma\, F_K}{A_T\, \sigma} \tag{6}$$

where $\Gamma = \frac{T\, F_T}{F}$ is the land share of output. Next, I use this technology framework to characterize BNF and GM soy technologies and make predictions about their diffusion process:

**Assumption 1:** *BNF soy is a land-augmenting and capital-biased technological change.*

The BNF soy technology improves yields in the Savanna through high investments in capital, as described in section II. Note that though the derivative of the marginal product of capital with respect to technology — the left-hand side of Equation (6) — is always positive, the effect of technical change on the marginal product of capital can be very large if the land share of output is large, marginal product of capital is large, and the technological factor $A_T$ is small. These properties describe agricultural production in the Savanna very well. In fact, there is clear evidence in the agricultural census dataset that land and capital are complementary in soy production.

Capital-biased technological change, such as BNF soy, increases the optimal level of capital and the profitability of contracting. Figure 3 illustrates this effect using the first-order condition of farmer profit maximization, where the farmer profit function simplifies to $\Pi = P\, F(T, K, A) - W\, K(\mathrm{A})$. The optimal level of working capital for soy production with technology $A$ and without contracting is $K_0^*$. Using technology $A$, the benefit of contracting is the additional profit represented by the area under the marginal revenue function and above the marginal cost function, between optimal capital levels $K_0^*$ and $K_1^*$. Capital-biased technological change shifts the marginal revenue function to the right. The profitability of adopting contract-bundled technological change can potentially be very large, as the optimal level of capital shifts to $K_2^*$. Equation (6) shows that the magnitude of the shift in the marginal revenue function depends on the technological factor of production $A_T$ and can be very large in the Savanna.

**Assumption 2:** *GM soy is a capital-augmenting (labor-saving) technological change.*

The main benefit of GM technology is to reduce the number of required pesticide applications, which reduces the amount of labor necessary to produce a fixed amount of soy. The effect of the GM technological change on the marginal product of capital is ambiguous, depending on the relative elasticities of substitution and the labor share of agricultural output. For detailed analysis, see Bustos, Caprettini, and Ponticelli, (2016). Given that the land share of output is consistently large in soy production, I assume that the GM technological change does not significantly affect the marginal product of capital.

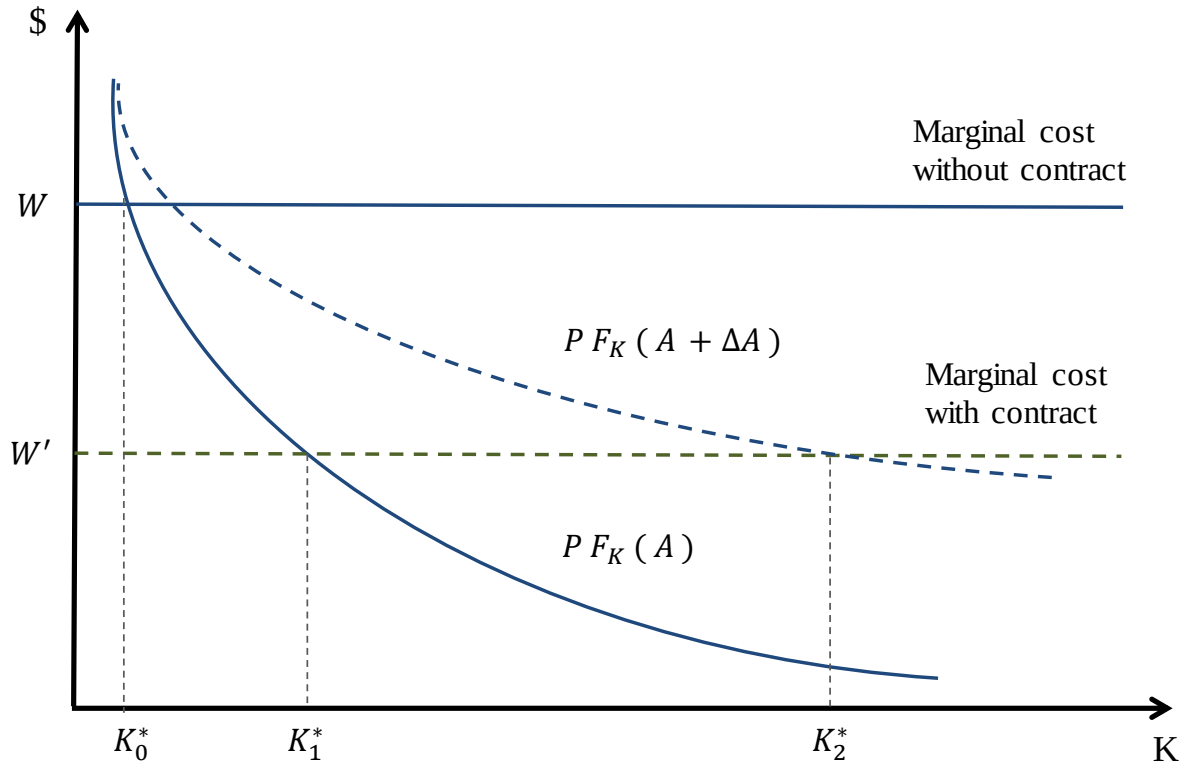


Figure 3. Farmer profit maximization with capital-biased technical change and contracting

## Optimal Choice of Contracting

For interlinkage contracts, Gangopaphiay and Sengupta (1987) have shown that it is possible to design an optimal contract that achieves a maximum potential combined profit of both farmers and traders. The intuition behind this optimal contract is that the trader imposes a "profit tax" on

the farmer equal to the ratio between the maximum potential profit and the maximum profit that the farmer can achieve with the same production technology. This model then assumes variation in only one element of the cost function: credit costs. The optimal contract is represented by:

$$profit\ tax\ on\ the\ farmer = \frac{\Pi^*_{Farmer}}{\Pi^*_{Max}} < 1 \tag{7}$$

This model assumes only a single trader. Without competition, the trader will design the contract such that the farmer only gets his opportunity cost of land, $\Pi^*_{Farmer}$ . Equation (7) thus highlights the significance of the farmer's opportunity cost in his choice of contracting. Farmers with very productive land are much less likely to contract, even in the case of technological change because the comparative cost advantage of the trading companies is much smaller for them. Once we incorporate technological change and allow for additional cost efficiencies from contracting resulting from the benefits of scale (derived from vertical integration), the definition of the optimal contract depends on changes in both the production and cost functions. In this more complex case, it is easier to model the choice of contracting in terms of net revenues, which combines changes in both the production and cost functions. Figure 4 illustrates the choice of contracting considering the relationship between technological change, soil, and climate characteristics, $A = A(Z)$. The bundled contract becomes relatively more profitable with complex and capital-intensive technologies, such as BNF soy, which were designed specifically for land with low natural soy productivity.

**Empirical Implications**

I now combine the theoretical framework described above with assumptions about technology to produce a set of implications to guide empirical analysis.

**Implication 1:** *The BNF soy technological change tends to dramatically increase the profitability of contracting, speeding up the diffusion of technology on the agricultural frontier.*

BNF was designed for Savanna soil, which has not only strong complementarity between capital and land, or low $\sigma$, but also low land productivity, or low $A_T$, large land share of output, or high $\Gamma$, and high marginal product of capital (low-intensity production system), or high $F_K$. BNF technological change therefore increases the marginal product of capital, following Equation (6),

especially on the agricultural frontier. Bundled contracts then become a profitable diffusion mechanism.

**Implication 2:** *Though GM soy technological change does not affect the profitability of contracting, it tends to diffuse rapidly among soy producers due to very low conversion costs.*

Implication 2 is a direct result of Assumption (2). GM soy tends to diffuse particularly fast among producers located in highly productive regions because of very low conversion costs. In contrast to BNF, GM soy is capital-augmenting, but not capital-biased, and does not significantly affect the profitability of contracting.

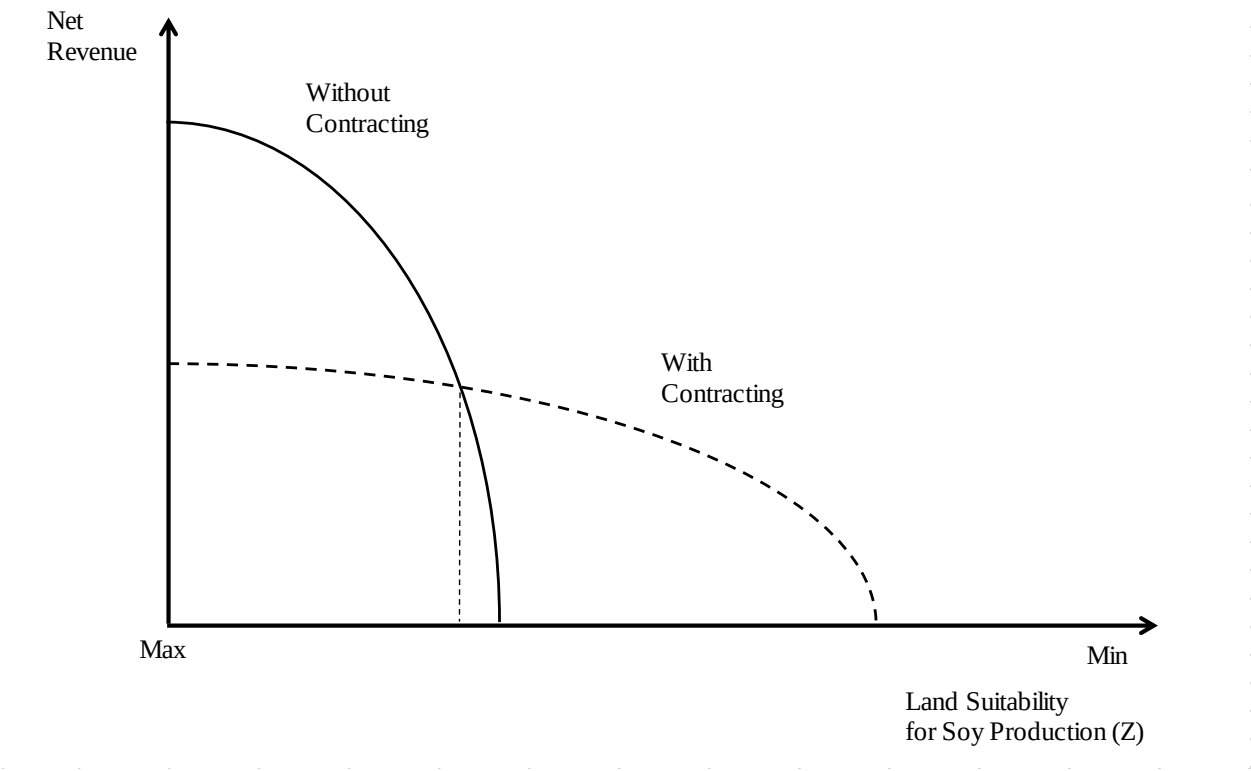


Figure 4. Choice of contracting: farmer net revenue of soy production with and without contracting as a function of land suitability for soy production.

**Implication 3:** *The combination of capital-biased technological change and contracting tends to increase the price elasticity of agricultural expansion.*

The price response of agricultural expansion can be represented by:

$$\frac{\partial S^*}{\partial P} = \Psi(S^*)\ [\frac{\partial\ \Pi^*(S^*,A)}{\partial P} + \frac{\partial\ \Pi^*(S^*,A)}{\partial A}\frac{\partial\ A}{\partial P}\ ] \tag{8}$$

where $S^*$ is the optimal share of land converted to soy production and $\Psi(S^*) = \frac{1}{\frac{\partial\ \Pi^*}{\partial S} - \frac{\partial\ OC}{\partial S}}$ captures variation in the productivity of land at the optimal agricultural share. Equation (8) is a direct application of the implicit function theorem for the optimal condition of land-use conversion, $\Pi^*(\ S^*, A\ , P) - OC\ (\ S^*, A\ ) = 0$, where $OC$ is the opportunity cost of the land. The price response modeled in Equation (8) may be decomposed into direct and indirect components. The indirect component represents technological change channel, the second term in brackets in Equation (8). In the case of the Brazilian Savanna, with a large endowment of land, land productivity decreases slowly as more land is added into production, so $\Psi(S^*)$ is relatively large. In low-income regions, the change in profits resulting from technological change, $\frac{\partial\ \Pi^*(S^*,A)}{\partial A}$, depends on the efficiency of economic institutions, such as credit and output markets, and farmer–trader contracts. The introduction of the bundled contract therefore increase $\frac{\partial\ \Pi^*(S^*,A)}{\partial A}$. The combination of BNF soy with contracting will increase the indirect component of the price response and the responsiveness of agricultural supply to price changes.

**Implication 4:** *Variations in the price of soy and the opportunity cost of land can look like technological change to the econometrician.*

Higher price increases in the Savanna can confound the effects of technological change on the profitability of contracting and its effect on agricultural expansion, as can be seen in the profit Equation (2). Local agricultural prices in developing countries can vary significantly due to differences in distance-to-market and often-poor transportation infrastructure. The Brazilian savanna is a good example: a productive agriculture frontier located over 1,000 km from main ports and large consumer markets along the Brazilian coast. It is possible that price increases largely drove the expansion of this agricultural frontier, with the effects of technological change

and contracting being relatively small. The identification of price effects is therefore an important component of an empirical analysis of technological change and contracting.

A lower opportunity cost of land increases the probability of contracting from the perspective of the trader, particularly in frontier regions, following Equation (7). Variation in the opportunity cost of land can also be correlated with technological change.[3] BNF soy was specifically developed for Savanna soil, and the first commercialized GM soy was designed for temperate production regions in the United States, with climate and soil characteristics similar to the Brazilian south. A significant challenge in the empirical analysis is to disentangle the effects of contracting and technological change from variations in price and the opportunity cost of land.

**Summary of Empirical Approach**

In this section, I use the theoretical framework described above to derive a simple baseline empirical model and to explain the main idea behind my identification approach. After that, I detail the main datasets.

I start my empirical analysis by modeling the choice of whether or not to contract, estimating Equation (1), using a univariate Probit model:

$$\Pr\{ I \} = \Phi [ \beta_0 + \beta_1 OC + \beta_2 \Delta P + \beta_3 \Delta A ] \tag{9}$$

The notation is the same as in the theoretical framework. $\Phi$ is the standard normal distribution. The parameter $\beta_3$ captures the effect of technological change on contracting, and the parameters $\beta_1$ and $\beta_2$ measure the potentially confounding effects of opportunity cost and changes in price, respectively. Estimating Equation (9) requires a proxy for technological change. My approach uses exogenous measures of land suitability for specific types of technology, either variations in soil characteristics or estimators of potential yield (Bustos, Caprettini, and Ponticelli, 2016). The key idea is that the profitability of technological change varies with soil and climate characteristics. Suitability measures, such as the potential yield indexes generated by FAO, capture this exogenous cross-sectional variation.

[3] There is clear evidence of a large migration of farmers, looking for cheaper land to expand production, from the southern states of Brazil to the Savanna in the 1970s and 1980s. Price increases after the market reforms of the 1990s could have led to additional migration to the Savanna.

Equation (9) is also useful for investigating Empirical Implication (4). The marginal effect of price on choice of contracting and technology using a Probit model is simply $\beta_2\phi(.)$, where $\phi(.)$ is the standard normal density function, making it straightforward to estimate the component of price elasticity due to technological change.

I then estimate the effect of contracting adoption on the change in agricultural outcomes, $\Delta Y$, using a first-differences model:

$$\Delta Y = \delta + \theta_1 \Delta P + \theta_2 I + \theta_3 OC + \Delta u \tag{10}$$

where $I$ is a dummy variable for contracting. The key parameter of interest is $\theta_2$, the effect of contracting adoption. Parameters $\delta$ and $\theta_3$ capture pre-existing trends in agriculture. Farmer time-invariant heterogeneity, such as soil and climate characteristics, distance to market and from input sources, and historical land-use, is differenced out. Equations (9) and (10) provide a simple and intuitive mechanism to test Implications (1) and (2), the combined effect of technology and contracting on agricultural outcomes. I use exogenous sources of variation specific to each type of technology to estimate Equation (9) and then use the fitted values—the predicted probabilities of contracting for a particular technology—as instruments for contracting in Equation (10). In order to compare my results with those in previous literature, I also estimate the reduced form of Equation (10), without the endogenous dummy variable.

I identify contracting effects by combining time variation due to the introduction of the new type of farmer–trader contract with cross-sectional variation in exogenous drivers of the profitability of technological change and contracting. The two key identification assumptions are as follows:

**Identification Assumption 1:** *The introduction of the new type of farmer-trader contract is exogenous.*

**Identification Assumption 2:** *Exogenous variation in soil suitability drives potential profitability of the new BNF contract, conditional on census block and time-state fixed effects.*

I test the robustness of my results using as instruments alternative measures of soil suitability and the distance from the closest lime mine as a source of variation in the conversion cost of BNF technology. Exogenous sources of variation in soil characteristics and in the conversion cost to new technologies are good candidates for instruments, because these drive the choice of

production technology, which directly affects the profitability of contracting. The proposed channel of identification can be represented schematically as follows:

$$\begin{cases} Soil\ suitability\ to\ technical\ change \\ conversion\ cost\ of\ technical\ change \end{cases} \Rightarrow \begin{matrix} Choice\ of\ Production \\ Technology \end{matrix} \Rightarrow \begin{matrix} Profitability\ of \\ Contracting \end{matrix}$$

Finally, I take advantage of the rich census dataset to test the proposed instruments in combination with sets of controls and fixed effects, using different subsamples of farmers based on land-use choice before and after the introduction of the new contract.

## 4. Data and Descriptive Statistics

In this section, I describe the three main datasets used in my empirical analysis: the Brazilian Agricultural Census produced by the Brazilian Institute of Geography and Statistics (IBGE, 1996; IBGE, 2006), the IIASA/FAO Global Agro-Ecological database (GAEZ) (IIASA/FAO,2012), and the Municipal Agricultural Production Survey, also maintained by IBGE (PAM, 2016). For each dataset, I present summarized descriptive statistics for the key variables. I focus particularly on the definitions of contracting and land suitability variables.

**Farm Data: Brazilian Agricultural Census Micro Dataset**

Every 10 years, IBGE surveys over five million farmers in Brazil, collecting detailed information on farmer characteristics and production systems, including production technology; output; land use; inputs; and the financial values of assets, revenues, and expenditures at the farm level. A subset of the IBGE Agricultural Census data is publicly available at the municipality level (there are approximately 5,500 municipalities in Brazil). Although access to the complete farm-level agricultural Census data is highly restricted because of confidentiality regulations, the dataset can be used for academic research at the IBGE data center (CDDI) in Rio de Janeiro, Brazil. Most of my empirical analysis was completed at the CDDI.

In this analysis, I connected 1.5 million commercial farms from the 1996 and 2006 Censuses at the census block level, generating a panel dataset of about 50,000 observations covering the entire country. Commercial farms were identified by using farm size and production value, following the standards defined by the Brazilian Agricultural Research Agency (Embrapa) (Alves et al., 2012). In Brazil, 1.5 million commercial farms, which represent about 27% of the

total in the country, produce more than 80% of the total agricultural output. The key variables used in the empirical analysis were soy harvested area, farm production value, farm land use, farm size, type of seed, and the destination of agricultural produce. Table 1 provides summary statistics for the key variables and decomposes soy expansion by the major production regions in Brazil. The area harvested with soy increased by 7.5 million hectares from 1996 to 2006. One-quarter of this expansion occurred in the South and 75% in the Savanna. The area harvested with soy under contract increased by approximately 4.5 million hectares, 89% of which occurred in the Savanna. By contrast, the area of GM soy harvested increased by 2.8 million hectares, with 79% of this increase in the South region. The sample is formed by 34,873 census blocks, covering an area of approximately 290 million hectares, of the major production regions of Brazil. The only excluded regions were the north-western area of the Amazon and the Northeast region. The average farm size is 180 hectares and the average census block size is approximately 8,000 hectares. Each census block consists of 40 farms on average.

Table 1. Descriptive Statistics – Soy Expansion Decomposition

| | All Production Regions | | | South | | Savanna | |
|---|---|---|---|---|---|---|---|
| Soy expansion: | 1996 (1) | 2006 (2) | Δ (3) | Δ (4) | % (4) / (3) | Δ (5) | % (5) / (3) |
| Quantity produced (million tons) | 19.2 | 41.2 | 22.0 | 5.6 | 25% | 16.0 | 73% |
| Area harvested (million ha) | 8.4 | 15.9 | 7.5 | 2.1 | 28% | 5.4 | 71% |
| Area contracted | 2.8 | 7.3 | 4.5 | 0.5 | 10% | 4.0 | 89% |
| Area harvested by type of seed: | | | | | | | |
| GM | 0.0 | 3.6 | 3.6 | 2.8 | 79% | 0.7 | 21% |
| Certified | 8.4 | 12.3 | 3.9 | (0.7) | -18% | 4.6 | 117% |
| Value of agricultural production ( 2006 Billion R$ ) | 82.7 | 119.8 | 37 | 6 | 17% | 20 | 53% |
| Observations - Number of census blocks | 34,873 | 34,873 | | 8,147 | | 13,789 | |
| Number of commercial farms (million) | 1.60 | 1.52 | | 0.30 | | 0.74 | |
| Total area (million ha) | 294 | 285 | | 33 | | 183 | |
| Average farm size (ha) | 184 | 188 | | 111 | | 245 | |

Notes: Data from the IBGE Agricultural Census micro dataset. The value of agricultural production includes value of crops and grazing products. Columns (1) and (2), all production regions, also include the Southeast region. Area contracted is based on a more general definition of contracting, using the destination of production variable from the IBGE Census. Savanna includes the Midwest region, the frontier MATOPIBA region, and the state of Minas Gerais. The number of farms, total area, and average farm size for the South and Savanna refer to 2006 data.

The Census micro dataset contains four variables that closely match the characteristics of the new farmer–trader contract. The Census identifies the destination of soy production by farm, differentiating between producing soy for consumers, cooperatives, government, industry, intermediaries, and others. It also identifies whether the farmer has debt with private companies, received technical assistance from private companies, and used the technological package observed for contracts in the Savanna, which includes certified seeds and lime for pH correction. I use combinations of these four variables to construct alternative proxy definitions of contracting. Definition A is the most general definition of contracting, based only on one variable, namely the destination of production, whereas the most restrictive definition, definition F, uses all four of the variables described above. Most results reported in this paper use the most restrictive definition of contracting, however, I find that the results are robust to the alternative definitions of contracting when the sample is restricted to the Brazilian Savanna.

To control for variations in the opportunity cost of land as well as in pre-existing trends in soy outcomes, I also integrate municipality level data from the Agricultural Census of 1985 to create variables for the baseline characteristics. These baseline characteristics include population density; income per capita; agricultural production value; farm size; land-use share for crop, soy, grazing, and natural vegetation; and distance measures to cities, ports, and lime mines.

**Soy Suitability Data: IIASA/FAO GAEZ**

FAO and IIASA combine climate and soil characteristics to estimate the potential yield of 154 different crops for millions of grid cells (0.5° by 0.5° latitude and longitude) covering the entire planet (IIASA/FAO, 2012; Nunn and Qian, 2011). IIASA and FAO compute the potential yield for each crop under three levels of management and input use as well as for rain-fed and irrigated farming. In this analysis, I only consider potential yield measures for rain-fed farming because less than 3% of agriculture production in the sample uses irrigation. I combine the IIASA/FAO measures of potential yield for soy and alternative crops such as sugarcane, rice, cotton, coffee, and corn with the Census micro dataset at the census block level, using a geographical information system. For the identification of technological change, I then use the differences in potential yield for the three levels of management and input use to construct proxies for the return on agricultural intensification (Bustos, Caprettini, and Ponticelli 2016). The three new differenced potential yield variables are $\Delta A\ (High - low)$, $\Delta A\ (High - medium)$, and

$\Delta A$ $(Medium - low)$, where high, medium, and low are the three levels of management and input use defined by IIASA/FAO. These differential potential yield measures, $\Delta A$, can be interpreted simply as the marginal value of agricultural intensification.

Figure 5 shows that both soy expansion and contracting expansion in Brazil vary with the potential yield measure under a high level of management and input use. There is a clear correlation between soy expansion and contracting expansion, consistent with empirical prediction 1 and the descriptive statistics in Table 1. The majority of soy expansion happened in the Savanna using BNF soy technology, which was designed for acidic and nutrient-deficient soils, as is the case in the Savanna.

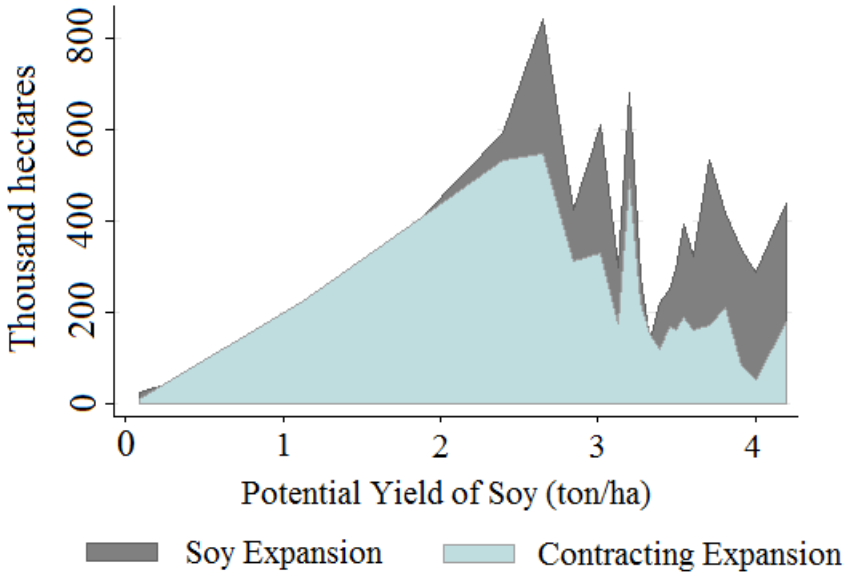


Figure 5. Distribution of soy expansion and contracting expansion in Brazil from 1996 to 2006 by the potential yield of soy production under a high level of management and input use.

To check the effectiveness of the crop suitability measures in predicting technological adoption, I also combine detailed soil and climate characteristics at the municipality level into the Census micro dataset, using data from Embrapa. The suitability measures are essentially estimates from the production functions modeled by IIASA and FAO. Figure 6 shows the relationship between the potential yield (medium – low) and nitrogen content of the soil, using a Binscatter plot for the

Census micro sample with 100 bins. The strong negative correlation between $\Delta A\ (Medium - low)$ and nitrogen content suggests that $\Delta A\ (Medium - low)$ should be a good predictor of the adoption of BNF soy that specifically targets land deficient in nitrogen.

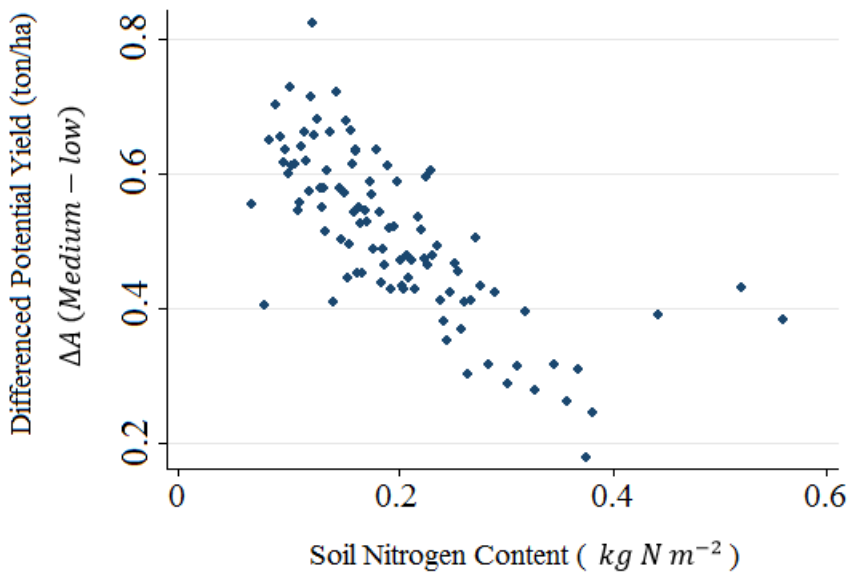


Figure 6. Correlation between $\Delta A\ (Medium - low)$ and the nitrogen content of soil. This graph is generated by a Binscatter regression to plot the relationship between potential yield and nitrogen.

Table 2 shows the correlations between the potential yield measures and soil and climate characteristics in Brazil. $\Delta A\ (High - medium)$ is a good predictor of technologies such as GM soy, originally designed for high productivity land, while $\Delta A\ (Medium - low)$ works well to predict the returns on technologies such as BNF. In my empirical analysis, I use variations in soil characteristics to complement and test the robustness of the soil suitability measures in predicting the potential return on adopting GM and BNF technologies.

Table 2. Descriptive Statistics – Potential Yield Production Function

| | | | Δ Potential Yield ( High - Medium ) | | Δ Potential Yield ( Medium - Low ) | |
|---|---|---|---|---|---|---|
| Soil and climate characteristics | Mean | Std. Dev. | (1) | (2) | (3) | (4) |
| Nitrogen | 0.17 | 0.08 | 1.01 *** | 0.47 *** | -0.23 *** | -0.68 *** |
| pH | 5.37 | 0.51 | 0.01 | 0.04 | 0.23 *** | 0.21 *** |
| Temperature Spring | | | -0.05 *** | -0.08 *** | 0.01 *** | 0.01 *** |
| Precipitation Spring | | | 4.18 *** | 3.93 *** | 0.40 *** | -2.31 *** |
| Constant | | | 2.76 *** | 3.53 *** | -0.82 *** | -0.23 *** |
| Sample: | | | | | | |
| Soy Expansion? | All | All | All | Yes | All | Yes |
| N | 34,873 | 34,873 | 34,873 | 5,917 | 34,873 | 5,917 |
| R2 | | | 0.21 | 0.34 | 0.13 | 0.30 |

Notes: Potential yield data from the FAO/IIASA GAEZ dataset. Potential yield is a function of climate, soil, and input levels. Differential potential yield measures the increase in soy tons per hectare once input level is increased. There are three levels of input in the GAEZ dataset: low, medium, and high. Data on soil characteristics from Embrapa (Embrapa, 2014). Climate data from the University of Delaware (Willmott and Matsuura, 2012). Spring season in Brazil refers to the months of September, October, and November, which is the planting season for soy in Brazil.

### Price Data: Municipal Agricultural Production Survey (PAM)

In addition to the Agricultural Census, IBGE conducts annual surveys with producers of major crops to track quantity produced, area planted and harvested, and average price to producer (hereafter referred to as spot prices) at the municipality level (IBGE, 2002; Hausman, 2012). Data collectors from IBGE allocated to different municipalities track the output and price variables monthly and compute weighted average estimates for annual productivity and spot prices in each municipality, generating a panel dataset that is publicly available and spans from 1990 to 2014 (IBGE, 2002). I use the PAM panel of spot prices to compute changes in expected prices before and after the introduction of the new contract. I also follow Hausman in computing a variable for changes in price risks, measured in terms of weighted deviations from average prices (Hausman, 2012), both before and after the introduction of the new contract.

Figure 7 shows the distribution of changes in expected prices for the two major soy producing regions in Brazil. The large changes in soy spot prices are the direct result of the introduction of the Kandir law in 1996 and the change in exchange rate policy in 1999, as described in Section 2.

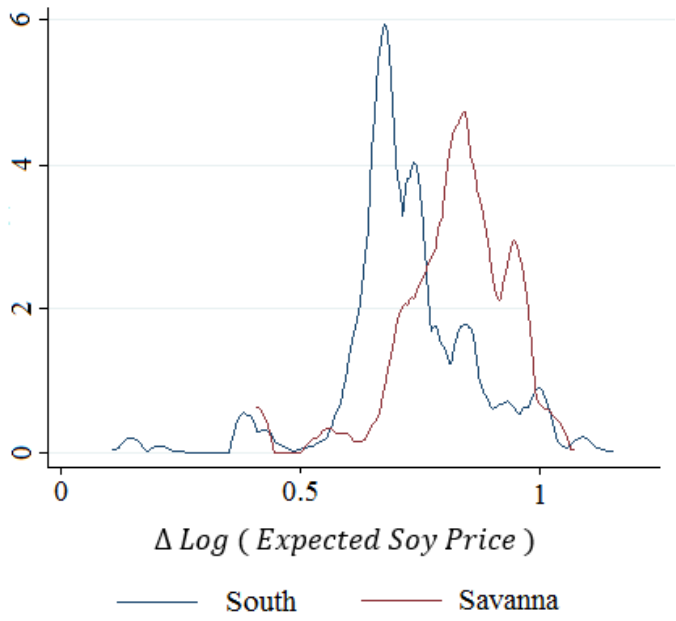


Figure 7. Density functions of the changes in the log of expected prices by region. Large price changes result from the introduction of the Kandir law in 1996 and change in exchange rate policy in 1999.

The spatial variation in price changes is driven by the large differences in transportation costs across the major production regions in Brazil and the differentiated local effect of the Kandir law. The producer spot price in a municipality can be represented by the equation:

$$P_{Spot} = (1-\tau) \times P_{Market} \times (Exchange\ Rate) - (1+\tau) \times TC \times (Distance) \qquad (11)$$

where $\tau$ is a local tax that varies with transportation route and is applied to the total value of sales, which includes production value plus profits and transportation services. $TC$ is transportation cost per km. In large producing regions, both changes in exchange rates and changes in the local ICMS tax will generate different rates of change, with larger percentage increases in frontier regions located at greater distances to ports and markets.

**Descriptive Analysis of Contracting**

I now use the integrated panel dataset detailed above to describe the importance of the new farmer–trader contract before presenting econometric results. Figure 8 illustrates the growth in total agricultural production value per hectare in the Savanna frontier, specifically in locations that produced soy in 2006 but not in 1996. The growth factor, agricultural production value per hectare in 2006 divided by agricultural production value in 1996, ranged from 1 to 10 in locations that did not contract. By contrast, about half of the locations that expanded soy with contracts experienced production value growth factors of 10 to 100. Several factors other than the adoption of contracting could be alternative causes of such large differences and extraordinary growth rates. The objective of the econometric analysis presented in the next section is to isolate the contracting effect.

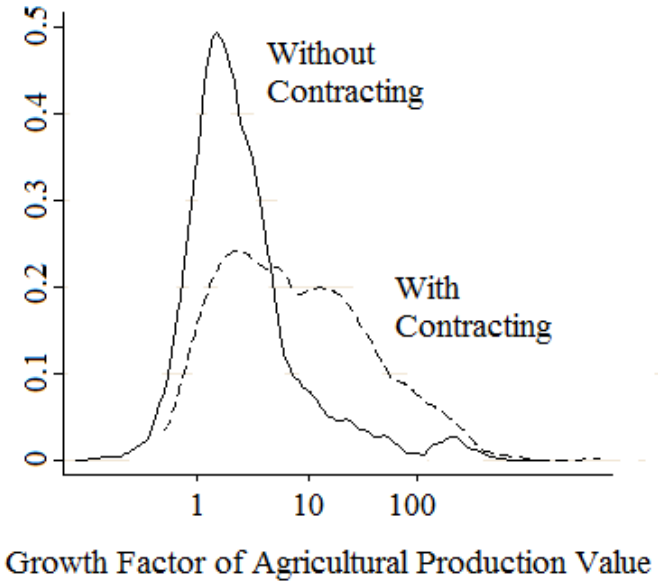


Figure 8. Distribution of the growth factor of agricultural production value per hectare from 1996 to 2006. Sample of locations in the Savanna frontier with soy expansion.

In my empirical analysis, I take advantage of the rich panel of Census data to investigate contracting effects for different definitions of contracting and various subsamples of farmers. Table 3 describes the empirical analysis, presenting the average statistics of the outcomes and census blocks' characteristics differentiated by locations that did or did not expand, and locations

which did or did not contract. The analyzed subsamples are described at the bottom of Table 3, based on the production of soy in 1996, contracting in 1996, and the expansion of soy production between 1996 and 2006. I show the statistics for two definitions of contracting, the more general definition, A, based on the destination of soy production and the more restrictive definition, F, based on all four variables that match the bundled contract.

Table 3. Descriptive Statistics – Variation in Outcomes and Census Blocks' Characteristics for the Choices of Soy Expansion and Contracting

| | Savanna | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Soy Expansion | | Contract Definition A | | Contract Definition A | | Contract Definition F | |
| | No | Yes | No | Yes | No | Yes | No | Yes |
| Median values of outcomes and characteristics | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| Outcomes: | | | | | | | | |
| Production value (R$/ha) | 220 | 418 | 198 | 190 | 183 | 190 | 179 | 228 |
| Change in production value per ha (%) | 8% | 83% | 11% | 123% | 64% | 123% | 82% | 255% |
| Capital value (R$/ha) | 276 | 498 | 252 | 322 | 284 | 322 | 307 | 325 |
| Soy expansion (ha) | 0 | 1,015 | 0 | 852 | 100 | 852 | 396 | 2,500 |
| Soy yield (tons/ha) | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.6 | 2.7 |
| Change in soy yield (%) | 16% | 20% | - | - | - | - | - | - |
| Characteristics: | | | | | | | | |
| Δ Log (Price) | 0.56 | 0.77 | 0.56 | 0.77 | 0.69 | 0.77 | 0.76 | 0.82 |
| Δ Pontential Yield (High - Medium) (tons/ha) | 2.36 | 2.37 | 2.35 | 2.19 | 2.24 | 2.19 | 2.22 | 2.17 |
| Δ Pontential Yield (Medium - Low) (tons/ha) | 0.49 | 0.63 | 0.49 | 0.60 | 0.61 | 0.60 | 0.60 | 0.55 |
| Distance to Lime mine (Km) | 160 | 167 | 163 | 231 | 175 | 231 | 197 | 269 |
| Log of production value in 1985 | -1.03 | -1.32 | -1.03 | -1.78 | -1.33 | -1.78 | -1.56 | -1.99 |
| Mechanic harvest (%) | 2% | 93% | 2% | 97% | 65% | 97% | 84% | 100% |
| No-Till farming (%) | 16% | 76% | 15% | 64% | 49% | 64% | 54% | 100% |
| pH Correction (%) | 1% | 75% | 1% | 70% | 39% | 70% | 54% | 100% |
| Sample: | | | | | | | | |
| Soy production in 1996? | All | All | No | No | No | No | No | No |
| Contracting in 1996? | All | All | No | No | No | No | No | No |
| Soy Expansion? | All | All | All | All | Yes | Yes | Yes | Yes |
| Observations - Number of census blocks | 12,386 | 1,403 | 12,004 | 392 | 236 | 392 | 564 | 64 |

Notes: Data from the IBGE Agricultural Census micro dataset. Contract definitions range from A to F, where A is a more flexible definition, based on the destination of production, and F is a more restrictive definition, based on the destination of production, debt with private companies, technical assistance with private companies, and the adoption of a technological package. The variables production value and soy yield are expressed in terms of mean values. The variable log of production value in 1985 is not presented in monetary values to avoid the distortionary effect of hyperinflation. This variable captures well the variability in the profitability of land before the period of study.

Agricultural production value per hectare increased by 83% in locations with soy expansion and 255% in frontier locations with both soy expansion and contracting. Price changes were higher in locations with both soy expansion and contracting, suggesting that price increases can influence the decision to expand both directly and indirectly by raising the profitability of contracting. The soil suitability measure $\Delta A\ (High - medium)$ does seem to affect expansion decisions in the Savanna, but there is a clear difference in $\Delta A\ (Medium - low)$ for places that expanded with contracts; these places tend to be located further from lime mines for all three cases presented in Table 3. The log of production value in 1995 captures the cross-sectional variation in the opportunity cost of land. Soy expansion with and without contracting tended to occur in locations with a lower opportunity cost of land. Finally, the technological indicators were consistently significantly higher in locations with both soy expansion without contracts and soy expansion with contracts.

The descriptive statistics presented above support the "bundling hypothesis," where the value of the bundled contract for the farmer tends to increase in locations less suitable for soy production, although more suited to BNF soy technology. Bundled contracts are also more favorable in locations further from main input sources, where the cost of technological conversion is higher. In summary, the benefit of bundling tends to increase in places where multiple barriers to technological adoption generate a hurdle too great for most farmers.

## 5. Empirical Results

I present evidence of contracting effects on agricultural expansion, agricultural productivity, and price responsiveness of soy expansion, in three steps. I first explicitly model the farmer's choice of expansion and contracting using a simple Probit model. Secondly, I estimate a reduced-form first-differences model with time-state fixed effects, similar to the models estimated by Bustos, Caprettini, and Ponticelli (2016) and Braganca, Assuncao, and Ferraz (2014), using suitability measures to identify the effect of the introduction of the new bundled contract. I also combine the Probit choice model with the reduced-form first-differences model to simulate the indirect effect of price changes on soy expansion, through the adoption of the bundled contract. I use a semi-parametric sieves estimator of the reduced-form first-differences model to demonstrate the robustness of the soy supply response and to graphically interpret the results. Finally, in the third

step of my empirical analysis, I estimate a structural model of contracting in the form of an endogenous dummy variable equation, where I instrument contracting with the fitted values of the Probit model for the choice of contracting.

I test the robustness of my results using a variety of controls for the opportunity cost of land and baseline characteristics. I test the model using time-state-biome fixed effects as well as time-mesoregion fixed effects. Brazil has 27 states and six biomes, and many states have multiple biomes. Brazil is divided geographically into 137 mesoregions. The time-state and time-mesoregion fixed effects play a very important role in the empirical analysis as they capture local variation in the trends of soy agricultural expansion. The more restrictive mesoregion-state fixed effects absorb most of the trends typically modeled in terms of baseline characteristics, but they also remove all variation in price changes. For the estimation of price elasticities, I use state-biome-time fixed effects combined with a set of baseline characteristics. I also test the robustness of the models by using alternative definitions of contracting and different subsamples of farmers based on their land-use choices before and after the introduction of the bundled contract.

**Choice of Expansion and Choice of Contracting**

The choice of soy expansion is modeled with the following Probit equation:

$$Pr\left\{ Expansion \right\} = \Phi\left[ \delta_0 + \delta_1 d_{UF} + \beta_1\, OC + \beta_2\, \Delta P + \beta_3\, \Delta A + \beta_4\, \Delta X \right] \qquad (12)$$

I use $\delta$ for the fixed effects coefficients. $X$ is a vector of baseline characteristics and other controls such as price changes of alternative crops, and the price risk variable described in Section 3. I break down the crop suitability variable into two parts, $\Delta A\ (High - medium)$ and $\Delta A\ (Medium - low)$, and I estimate crop suitability effects using a quadratic function. Table 4 presents the estimated model for the entire country and for the two major production regions, with and without baseline characteristics and time-state-biome fixed effects.

Table 4. Choice of Soy Expansion: $Pr\left\{ Expansion \right\} = \Phi\left[ \delta_0 + \delta_1 d_{UF} + \beta_1\, OC + \beta_2\, \Delta P + \beta_3\, \Delta A + \beta_4\, \Delta X \right]$

| | Country | | South | | Savanna | |
|---|---|---|---|---|---|---|
| Variables | ( 1 ) | ( 2 ) | ( 3 ) | ( 4 ) | ( 5 ) | ( 6 ) |
| ΔLog(EP) | 1.810*** | 0.913*** | 0.780** | 0.310 | 2.818*** | 2.501*** |
| ΔA *(high - medium)* | -0.054 | 0.296*** | 0.308* | 0.597** | -0.092 | 0.182 |
| ΔA *(high - medium) squared* | 0.130*** | -0.017 | -0.000 | -0.097** | 0.066 | 0.017 |
| ΔA *(Medium - Low)* | 1.682*** | 0.793*** | 1.078*** | 0.150 | 2.427*** | 3.222*** |
| ΔA *(Medium - Low) squared* | -0.603*** | -0.435** | -0.366 | -0.046 | -1.253*** | -1.702*** |
| OC: Log Production Value per ha 1985 | 0.112*** | -0.059 | 0.189*** | -0.289*** | 0.168** | -0.397** |
| Baseline Characteristics | No | Yes | No | Yes | No | Yes |
| State Biome fixed effects | No | Yes | No | Yes | No | Yes |
| Observations (census blocks) | 34,357 | 30,299 | 8,147 | 7,949 | 2,445 | 2,444 |

Notes: *** p<0.01, ** p<0.05, * p<0.1 . All standard errors clustered at Municipio level.

Marginal Effects by quantile of ΔA Medium - Low :

| | | | | | | |
|---|---|---|---|---|---|---|
| Price | | | | | | |
| *1st quantile* | 0.538*** | 0.292*** | 0.288** | 0.098 | 0.418** | 0.375** |
| *5th quantile* | 0.630*** | 0.300*** | 0.299** | 0.102 | 0.871*** | 0.698*** |
| *9th quantile* | 0.638*** | 0.313*** | 0.302** | 0.108 | 0.964*** | 0.752*** |
| ΔA *(Medium - Low)* | | | | | | |
| *1st quantile* | 0.459*** | 0.222*** | 0.367*** | 0.051 | 0.306*** | 0.411*** |
| *5th quantile* | 0.401*** | 0.135*** | 0.290*** | 0.063 | 0.407*** | 0.479*** |
| *9th quantile* | 0.245*** | 0.028 | -0.066 | 0.079 | 0.125* | 0.126* |

The marginal effects of price and crop suitability on the probability of expanding are shown at the bottom of Table 4. These marginal effects are reported for different quantiles of $\Delta A\ (Medium - low)$.

The price effects estimated are statistically and economically significant in all models except for model (4), because the time-state-biome fixed effects absorbs most of the variability in price changes. Price effects are twice as large in the Savanna because of the indirect effect of price changes in the adoption of the bundled contract with BNF technology. The marginal effect of price changes on the probability of expansion in the Savanna increases with quantiles of $\Delta A\ (Medium - low)$. The marginal effect of price increases from 0.375 in the first quantile to 0.752 in the ninth quantile [Table 4, column (6)].

The effects of the crop suitability measures are clearly differentiated by region, as expected. For the country model, both $\Delta A\ (High - medium)$ and $\Delta A\ (Medium - low)$ have significant effects on the probability of expansion. Nevertheless, the probability of soy expansion is driven only by $\Delta A\ (High - medium)$ [column (4)] which captures the adoption of GM soy in the South.

By contrast, the probability of soy expansion is driven by $\Delta A\ (Medium - low)$ in the Savanna, which captures the effects of the adoption of the bundled contract with BNF technology.

The choice of soy contracting is modeled with the following Probit equation:

$$Pr\left\{ Contracting \right\} = \Phi\left[ \tilde{\delta}_0 + \tilde{\delta}_1 d_{UF} + \tilde{\beta}_1\, OC + \tilde{\beta}_2\, \Delta P + \tilde{\beta}_3\, \Delta A + \tilde{\beta}_4\, \Delta X \right] \qquad (13)$$

The crop suitability measure $\Delta A\ (Medium - low)$ is a robust predictor of contracting. Table 5 reports the results for the choice-of-contracting model [Equation (13)] estimated for the entire country and for the Midwest region of the Savanna. Columns (1) and (4) show the results for all locations that did not have any form of contracting in 1996. Columns (2) and (5) show the results for the frontier locations and columns (3) and (6) show the results for frontier locations with soy expansion. I found that the crop suitability measure $\Delta A\ (Medium - low)$ is an excellent predictor of contracting in all samples, for all contracting definitions and sets of controls, and for models with mesoregion fixed effects.

Table 5. Choice of Contracting: $Pr\left\{ Contracting \right\} = \Phi\left[ \tilde{\delta}_0 + \tilde{\delta}_1 d_{UF} + \tilde{\beta}_1\, OC + \tilde{\beta}_2\, \Delta P + \tilde{\beta}_3\, \Delta A + \tilde{\beta}_4\, \Delta X \right]$

| | Country | | | Midwest Savanna | | |
|---|---|---|---|---|---|---|
| Variables | ( 1 ) | ( 2 ) | ( 3 ) | ( 4 ) | ( 5 ) | ( 6 ) |
| ΔLog(EP) | 0.743*** | 1.824*** | 2.223*** | 1.195* | 2.829*** | 4.155*** |
| ΔA *(high - medium)* | 0.193 | 0.020 | -0.135 | -0.116 | -0.340 | -0.444 |
| ΔA *(high - medium) squared* | 0.007 | 0.029 | 0.003 | 0.132 | 0.110 | 0.095 |
| ΔA *(Medium - Low)* | 2.379*** | 2.258*** | 2.195*** | 5.739*** | 5.848*** | 3.671** |
| ΔA *(Medium - Low) squared* | -1.800*** | -1.489*** | -1.695*** | -3.754*** | -4.480** | -2.887** |
| OC: Log Production Value per ha 1985 | 0.473*** | 0.024 | 0.054 | 0.639*** | 0.272 | 0.263 |
| Population density 1985 | -0.473*** | -0.270*** | -0.113 | -0.530*** | -0.374* | -0.152 |
| State x Biome fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Sample: | | | | | | |
| Soy production in 1996? | All | No | No | All | No | No |
| Contracting in 1996? | No | No | No | No | No | No |
| Soy Expansion? | All | All | Yes | All | All | Yes |
| Observations (census blocks) | 14,853 | 10,705 | 1,747 | 1,857 | 1,544 | 299 |

Notes: *** p<0.01, ** p<0.05, * p<0.1 . All standard errors clustered at Municipio level.

Marginal Effects by quantile of ΔA Medium - Low :

| | | | | | | |
|---|---|---|---|---|---|---|
| Price | | | | | | |
| *1st quantile* | 0.069** | 0.039*** | 0.175*** | 0.014 | 0.0326 | 0.459 |
| *5th quantile* | 0.150** | 0.115*** | 0.443*** | 0.101 | 0.163** | 0.894*** |
| *9th quantile* | 0.120** | 0.133*** | 0.356*** | 0.134 | 0.105*** | 0.549** |
| ΔA *(Medium - Low)* | | | | | | |
| *1st quantile* | 0.184*** | 0.041*** | 0.146*** | 0.054* | 0.052* | 0.408* |
| *5th quantile* | 0.153*** | 0.058*** | 0.132* | 0.197*** | 0.102** | 0.221 |
| *9th quantile* | -0.165*** | -0.042** | -0.170*** | -0.140** | -0.098** | -0.254* |

The magnitude of the effects of the opportunity cost of land, population density, and state-time fixed effects decrease as we restrict the sample. These variables have a sorting effect, differentiating between locations that are completely unsuitable for farming and traditional production regions for more specialized crops such as coffee, orange, and sugarcane. Restricting the model to the Savanna eliminates much of the heterogeneity in the opportunity cost of land, a potential confounding factor for the contracting effects. Table 5 shows that, in general, the marginal effects of prices and $\Delta A\ (Medium - low)$ on the probability of contracting are higher in the Savanna. The barriers to technology diffusion are typically much lower in the South of Brazil than in the agricultural frontier. The South of Brazil is more developed, closer to large markets and ports, and has better infrastructure. The larger marginal effects of crop suitability and price changes are consistent with the hypothesis that bundling contracts are more valuable for farmers in the least developed regions faced with multiple constraints to technology adoption.

**Contracting and Price Effects on Soy Expansion: First-differences Results**

In this subsection, I estimate the reduced-form version of Equation (10), without an endogenous dummy variable. I use this analysis to compare my results with the previous literature and to investigate the effect of contracting on the price elasticity of agricultural expansion, testing Implication (3) (section 3, page 22).

The reduced-form empirical model for soy area expansion is:

$$Area_{it} = \delta_0 + \delta_1 t + \delta_2 d_{UF} t + \theta_1 P_{mt} + \theta_2 \Delta A_i + \theta_3 \Delta A_i t + \theta_4 OC_{it} + \theta_5 X_{it} + \alpha_i + u_{it} \quad (14)$$

where the notation is the same as in the theory section. $t$ is a dummy variable for time period: 0 for 1996 and 1 for 2006. Time-invariant census block heterogeneity is captured by $\alpha_i$, and includes soil and climate characteristics, historical land use in census block $i$, and distance to markets, ports, and major sources of inputs such as lime mines. Time-variant unobserved heterogeneity is represented by the error term $u_{it}$. Equation (14) is useful for interpreting the results. The two parameters of interest are $\theta_3$, which captures the change in the effect of crop suitability due to the introduction of the new bundled contract, and $\theta_1$, which captures price effects on soy harvested areas. With two time periods, the fixed effects model of Equation (14) is

equivalent to a simple first-differences model where time-invariant heterogeneity $\alpha_i$ is differenced out.

The actual model being estimated is the first-differences equation:

$$\Delta Area_i = \delta_1 + \delta_2 d_{UF} + \theta_1 \Delta P_i + \theta_3 \Delta A_i + \theta_4 \Delta OC_{it} + \theta_5 \Delta X_{it} + \Delta u_i \qquad (15)$$

I also estimated a sieves semi-parametric version of Equation (15) to explore the large heterogeneity of the Census micro dataset, test the robustness of the acreage supply function, represented by Equation (15), and provide a simple graphical interpretation of the price and contracting effects. For details on sieves models and estimation, see Chen (2007).

The sieves first-differences model is

$$\Delta Area_i = \delta_1 + \delta_2 d_{UF} + G(\Delta P_i) + \theta_3 \Delta A_i + \theta_4 \Delta OC_{it} + \theta_5 \Delta X_{it} + \Delta u_i \qquad (16)$$

The price response function in Equation (16), $G(\Delta P_i)$, is unknown, so I use the sieves approximation:

$$G_k(\Delta P_i, \tilde{\theta}_3) = \sum_{j=0}^{a} \Delta P^j \tilde{\theta}_{jk} + \sum_{j=1}^{m} \theta_{j+m} (\Delta P - v_j)^a \, 1[\Delta P \geq v_j] \qquad (17)$$

The sieves approximation is a polynomial spline where $a$ is the order of the polynomial, $m$ is the number of knots, and $v_j$ represents the $j^k$ knot. In essence, the model in equation (17) is splitting the support of the price changes into $m$ splices and using a different polynomial approximation for each segment. The semi-parametric sieves model with splines can be easily estimated by using least squares. Figure 9 presents the fitted values from the sieves acreage response function. The vertical axis shows prices changes in terms of differences in the log of expected prices and the horizontal axis measures soy expansion in hectares. Every dot in Figure 9 is one census block in Brazil. The different diagonal lines represent response functions for specific states, capturing the effect of state-time fixed effects that shifts the state response functions. The blue, yellow, and green dots are the census blocks located in the South, Savanna, and those with soy expansion contracted using the bundled contract, respectively.

The sieves acreage response function presented in Figure 9 graphically illustrates the key aspects of this empirical analysis. First, a flattening of the response curve is evident as we move from the South region to the Savanna. The last diagonal line on the right is the state of Mato Grosso, located at the frontier of the Amazon forest. The technology-driven soy expansion in the Savanna significantly increased the price elasticity of soy supply in Brazil. The concentration of green dots in the left part of the graph over the Savanna region represents the new frontier of soy expansion in the northern region of the Savanna, demonstrating how contracting helps promote development in a low-income region. The sieves response function also clearly illustrates the importance of the time trend fixed effects at the state level. The time-state fixed effects combined with the census block variation in crop suitability explain a significant part of the variation in agricultural outcomes, after we difference out time-invariant census block heterogeneity.

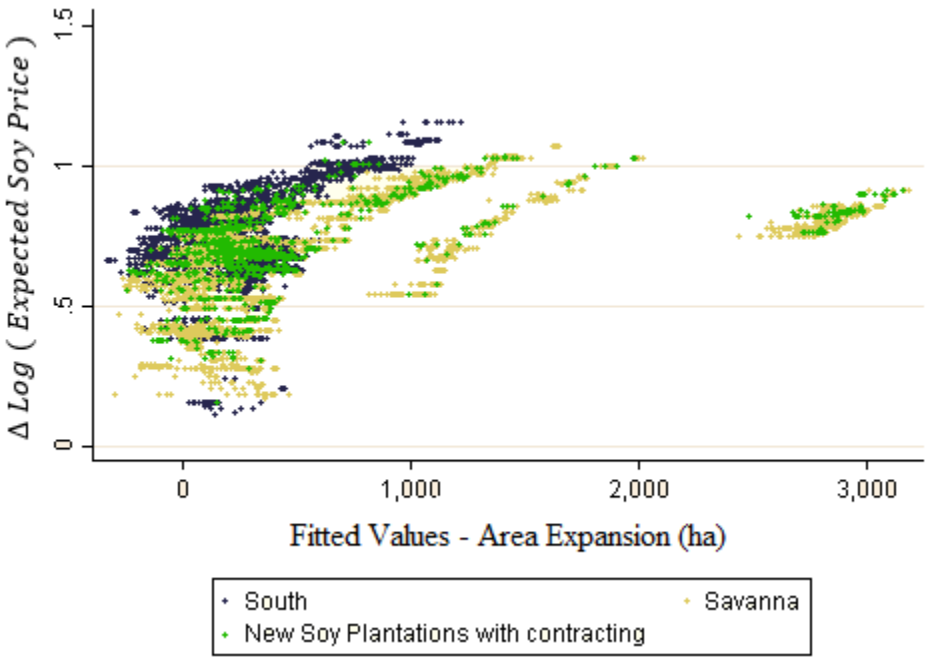


Figure 9. Sieves acreage response function for soy expansion in Brazil. The different diagonal response functions represent different states in Brazil. The green dots represent census blocks with new soy plantations using the new bundled contract

Table 6 presents the results from the estimation of the parametric expansion function [Equation (15)]. I present the results for two outcome variables that measure soy expansion: $\Delta\, Soy\ Area$, which measures acreage expansion in hectares in each census block, and $\Delta\, Soy\ Area\ Share$,

which measures the change in the share of soy harvested area in each census block. The denominator of $\Delta\, Soy\ Area\ Share$ is the total farm area in the census block. I present results for the country and major producing regions, including specifications using state-biome-time fixed effects and mesoregion-time fixed effects.

I find that crop suitability $\Delta A\ (Medium - low)$ has a significant effect on soy expansion in the Savanna, while crop suitability $\Delta A\ (High - medium)$ has a significant effect on soy expansion in the South, consistent with the results from the choice models. The marginal effect of $\Delta A\ (Medium - low)$ ranges from 620 to 1,233 hectares in the first quantile of $\Delta A\ (Medium - low)$ and from 127 to 558 hectares at the median of $\Delta A\ (Medium - low)$. The marginal effect of $\Delta A\ (Medium - low)$ on $\Delta\, Soy\ Area\ Share$ in the first quantile of $\Delta A\ (Medium - low)$ in 0.03. The marginal effect decreases at higher quantiles following the quadratic functional form estimated. In the South, the marginal effect of $\Delta A\ (High - medium)$ in the first quantile of $\Delta A\ (High - medium)$ is 0.01. Bustos, Caprettini, and Ponticelli (2016) estimate a marginal effect of $\Delta A\ (High - medium)$ of about 0.02 for Brazil, which is close to my estimates for the South region where farmers have rapidly adopted GM soy. However, my estimates for the Savanna are much higher because I explore the Census micro dataset to model the effect of BNF expansion, the most important technology for soy expansion in the Savanna, and the introduction of the new bundled contract.

My estimates for the long-run price elasticity of soy are consistent with the Hausman estimates (Hausman, 2012). Table 6 presents the estimated price elasticities for Brazil and major soy production regions. I find large heterogeneity in price responses across Brazil and within major production regions, especially in the Savanna. I combine the choice model for soy expansion with estimates for the conditional expected soy expansion to simulate how price elasticities vary with crop suitability $\Delta A\ (Medium - low)$. I find that after including the baseline characteristics and mesoregion fixed effects, the selection bias component of the conditional expected soy expansion becomes insignificant.

Table 6. First-differences Model: $\Delta\, Area \;=\; \delta_1 + \delta_2 d_{UF} + \;\theta_1 \Delta P + \;\theta_3\, \Delta A + \theta_4 \Delta OC + \theta_5 \Delta OC$

| | Δ Soy Area | | | | | | Δ Soy Area Share | | |
|---|---|---|---|---|---|---|---|---|---|
| | Country | | South | | Savanna | | Country | South | Savanna |
| Variables | ( 1 ) | ( 2 ) | ( 3 ) | ( 4 ) | ( 5 ) | ( 6 ) | ( 7 ) | ( 8 ) | ( 9 ) |
| ΔLog(EP) | 646** | 53 | 537** | 439* | 1,480*** | 136 | 0.041** | 0.087*** | 0.002 |
| ΔA *(high - medium)* | 122*** | 129*** | 112 | 217*** | -180 | -187 | 0.003* | 0.037*** | -0.013** |
| ΔA Sq *(high - medium)* | -47*** | -56*** | -26 | -67*** | 58 | 44 | -0.001* | -0.011*** | 0.003 |
| ΔA *(medium - Low)* | 662*** | 475*** | 773*** | -69 | 1,556*** | 855*** | -0.002 | -0.020 | 0.054** |
| ΔA Sq *(medium - Low)* | -640*** | -625*** | -483*** | -290 | -1,008*** | -735*** | -0.010*** | -0.046* | -0.064*** |
| OC: Log production value per ha 1985 | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| OC: ΔA other crops | No | Yes | No | Yes | No | Yes | Yes | Yes | Yes |
| State x Biome fixed effects | Yes | No | Yes | No | Yes | No | No | No | No |
| Meso region fixed effects | No | Yes | No | Yes | No | Yes | Yes | Yes | Yes |
| Observations (census blocks) | 33,316 | 34,357 | 7,952 | 8,147 | 2,172 | 2,172 | 33,589 | 7,913 | 2,172 |
| R2 | 0.060 | 0.093 | 0.011 | 0.030 | 0.110 | 0.157 | 0.176 | 0.112 | 0.189 |

Notes: *** p<0.01, ** p<0.05, * p<0.1 . All standard errors clustered at Municipio level.

Long-run price elasticity:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| First differences | 1.119*** | | | 1.317** | 3.549*** | | | | |
| Hausman, 2012 | 1.6 | | | 0.7 - 3.5 | 2.3 - 6.9 | | | | |

Figure 10 shows the relationship between the price elasticity of soy expansion on the vertical axis and the crop suitability measure $\Delta A\ (Medium - low)$ represented in terms of quantiles on the horizontal axis. Most of the variation in price elasticity is explained by changes in the soy suitability measure. Census blocks with higher soy suitability have a higher probability of adopting the bundled contract with BNF technology and higher price elasticity.

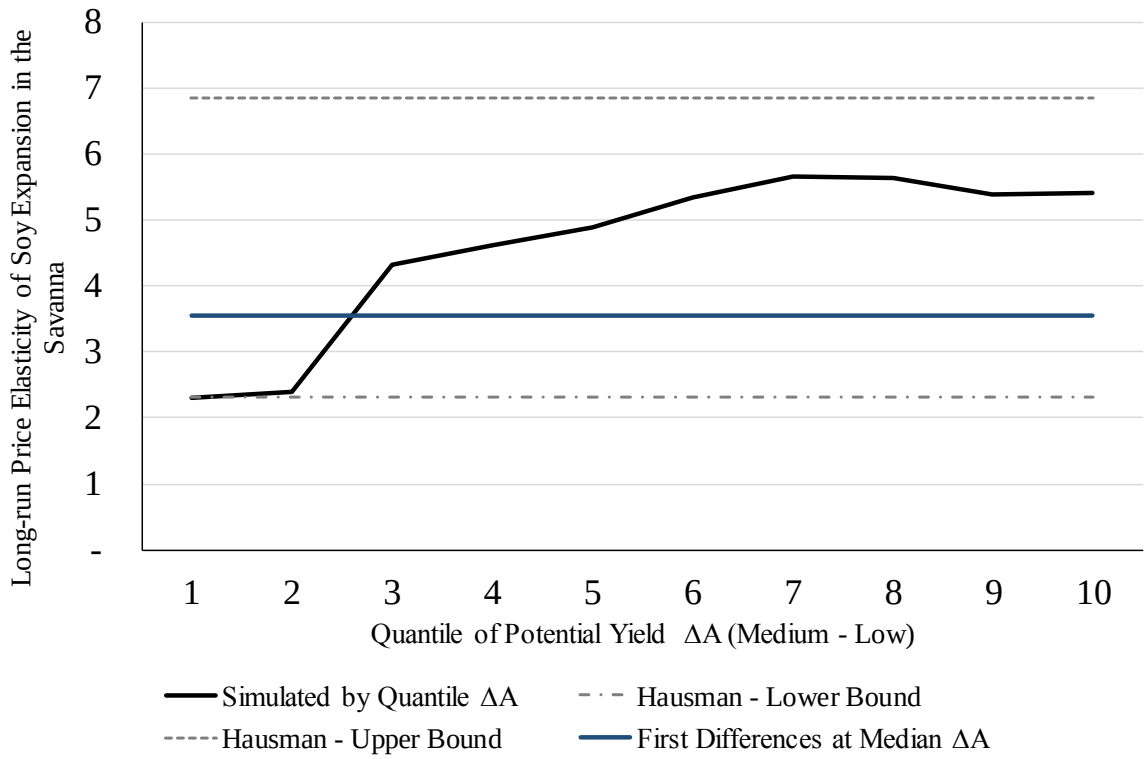


Figure 10. Relationship between the price elasticity of soy expansion and crop suitability $\Delta A\ (Medium - low)$. Crop suitability $\Delta A\ (Medium - low)$ drives the probability of adopting the new bundled contract. Higher suitability increases contracting and price responsiveness.

The effect of the introduction of the bundled contract, captured by the variation in soy suitability $\Delta A\ (Medium - low)$, explains most of the variation in price response. Even more impressive is the large sensitivity of the price elasticity to the propensity of contracting. The price elasticity of soy expansion more than doubles, increasing from 2.3 to 5.6, with increases in $\Delta A\ (Medium - low)$, and most of this increase is concentrated in the first quantiles. I also simulated the direct

effect of price on the conditional expectation of soy expansion in the Savanna and found it to be statistically insignificant. These results indicate that the mechanism behind the price responsiveness of soy expansion in the Savanna is the technology diffusion of BNF soy facilitated by the introduction of the new bundled contract. This result also suggests that the low long-run estimates of the price elasticity of agricultural supply are likely much more a direct reflection of the institutional barriers to technology adoption than a response to changes in the relative profitability of alternative land uses.

This result has important policy implications because many land-use policies designed to promote agricultural expansion or protect natural vegetation are implemented in the form of price incentives. The actual cost-effectiveness of these policies therefore significantly depends on spatial and time variation in the availability of economic institutions that drive technology adoption in developing countries.

**Contracting Effects on Soy Expansion: IV Results**

The structural version of the first-differences model represented by Equation (15) is

$$\Delta Y_i = \delta_1 + \delta_2 d_{UF} + \beta_1 \Delta P_i + \beta_3 I_i + \beta_4 \Delta OC_{it} + \beta_5 \Delta X_{it} + \Delta u_i \qquad (17)$$

where the parameter of interest is $\beta_3$, the effect of contracting on outcome $\Delta Y_i$ . I estimate Equation (17) for several outcomes, including soy expansion, change in soy area share, change in the total value of agricultural production, change in total land allocated to agriculture, and the adoption of complementary technologies such as the corn-soy multiple season production system. Equation (17) is the outcome equation of a structural model that also includes a participation equation. In my analysis, the participation equation is represented by the choice of contracting, Equation (13). I estimate Equation (17) using two-stage least squares, where $I_i$ is instrumented with the fitted values of the Probit model for contracting [Equation (13)].

There are several advantages to using fitted values to instrument an endogenous dummy variable in the outcome equation (Wooldridge, 2010). One important robustness property of this procedure is that the Probit equation does not need to be correctly specified. The estimation

procedure does not rely on the parametric assumption for the conditional density function, a normal density function in the case of the Probit model. Further, the fitted values from the Probit equation take into consideration the non-linear nature of the choice variable, and standard errors are asymptotically valid (Wooldridge, 2010). Finally, crop suitability is a strong predictor of the choice of contracting, and I include additional instruments in the participation equation, such as measures of soil characteristics, namely nitrogen content and soil pH, which drive the suitability for BNF technology adoption, and a measure of distance to lime mines, which drives farmers' conversion costs to BNF soy. I test the model with combinations of all of these instruments.

Table 7 reports the estimation results for the IV soy expansion model, Equation (17). I report the estimated results for the Savanna region and for the three subsamples of farmers: (1) frontier farmers who did not produce soy in 1996, (2) all locations where there was soy expansion between 1996 and 2006, and (3) all locations that produced soy in 1996 and expanded production in the period of study. I present the results for models using crop suitability as instruments and for models that use only soil characteristics and distance to lime mine as instruments.

All models account for controls for the opportunity cost of land, including crop suitability variables for alternative crops measured at the census block level, baseline characteristics, and state-biome-time fixed effects. For the soy area expansion models, I test specifications with controls for census block size and farm size. I find the results to be robust to the inclusion of mesoregion fixed effects, although I lose price variability with these specifications. Finally, Table 7 also contrasts the OLS and IV estimates for contracting effects.

I find large and statistically significant effects of contracting on soy expansion in all samples. As expected, the effects are much larger for frontier locations because of the selection effect of contracting on expansion. Contracting increases soy expansion in frontier locations by about 2,500 hectares, or about 20 percent of the size of an average census block. The contracting effects are slightly smaller as I restrict the sample to locations that expanded from 1996 to 2006. I find that the rich set of fixed effects and controls capture most of the selection mechanism of soy expansion. For locations with soy expansion, the contracting effect on soy expansion is about 1,800 hectares. Columns (5) and (6) report the results for the more restricted sample of farmers that already produced soy in 1996 and expanded production in 2006.

Table 7. IV Regressions of Soy Expansion: $\Delta Y_i = \delta_1 + \delta_2 d_{UF} + \beta_1 \Delta P_i + \beta_3 I_i + \beta_4 \Delta OC_{it} + \beta_5 \Delta X_{it}$

Contracting ($I$) is instrumented with the fitted values from Probit model for contracting choice.

| | Δ Soy Area ( Savanna ) | | | | | |
|---|---|---|---|---|---|---|
| | Frontier | | All locations with soy expansion | | Soy Producers who expanded | |
| Variables | ( 1 ) | ( 2 ) | ( 3 ) | ( 4 ) | ( 5 ) | ( 6 ) |
| I: Contracting - IV | 2,498*** | 2,534*** | 1,904*** | 1,758*** | 961.5** | 945.7** |
| I: Contracting - OLS | 1,535*** | 1,535*** | 1,060*** | 1,043*** | 1,017*** | 1,016*** |
| *Exogenous variables:* | | | | | | |
| OC - Potential yield alternative crops | Yes | Yes | Yes | Yes | Yes | Yes |
| Baseline Characteristics | Yes | Yes | Yes | Yes | Yes | Yes |
| State x Biome fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| *Instruments in probit first stage:* | | | | | | |
| ΔA | Yes | No | Yes | No | Yes | No |
| N and pH | Yes | Yes | Yes | Yes | Yes | Yes |
| Distance to Lime mine | Yes | Yes | Yes | Yes | Yes | Yes |
| Sample: | | | | | | |
| Soy production in 1996? | No | No | All | All | Yes | Yes |
| Soy Expansion? | All | All | Yes | Yes | Yes | Yes |
| Observations (census blocks) | 3,582 | 3,582 | 642 | 642 | 203 | 203 |
| F-Stat first stage | 15 | 14 | 28 | 18 | 21 | 20 |
| R2 OLS | 0.21 | 0.21 | 0.34 | 0.34 | 0.39 | 0.39 |

Notes: *** p<0.01, ** p<0.05, * p<0.1 . All standard errors clustered at Municipio level.
Contracting is instrumented with the fitted value of the Probit model for contracting choice. Opportunity cost variables are log of production value per hectare in 1985 and potential yield for alternative crops sugarcane, coffee, and cotton. Baseline characteristics are density and income per capita in 1985, and log of farm size in 1985. Additional controls are changes in prices of alternative crops and change in price volatility.

This is an important set of farmers, firstly because it represents a more homogeneous group and secondly because a large fraction of soy expansion in the Savanna occurred in census blocks that already produced soy in 1996. Even in the subset of soy producers, the effect of contracting is large and statistically significant, about 1,000 hectares of soy expansion.

There is a significant difference between the OLS and IV estimates for the effect of contracting but this difference disappears as we restrict the sample to soy producers in 1996. The difference between the OLS and IV estimates is consistent with the existence of unobserved productivity shocks, $\Delta u$, that increase the profitability of expansion by increasing the productivity of the farmer, and therefore reduce the value of the bundled contract.

The bundled contract is more valuable in locations where there are multiple barriers to the adoption of BNF technology. A productivity shock that eliminates a few of these barriers, for example a specific program or policy implemented by the local government, would increase the profitability of soy expansion and reduce the propensity for contracting. In the case of soy producers who already expanded [columns (5) and (6) in Table 7] the OLS and IV contracting effects are not statistically different.

I also estimate variations of Equation (17) by using quantile least squares and IV quantile least squares (Chernozhukov and Hansen, 2005) to examine the influence of extreme observations on the contracting effects. I find that the reported results in Table 7 are close to median estimates. The quantile models also show that the difference in estimates between OLS and IV increases for higher unobserved shocks, consistent with the bundling hypothesis.

**Simulation of Contracting Contribution to Soy Expansion: IV Results**

I use the IV first-differences model of Equation (17) to measure the contribution of the new bundled contract to soy expansion in the Brazilian Savanna. I simulate soy expansion in the different subsamples of Savanna farmers by using the Census micro data and the most conservative specification of the IV model, which uses mesoregion fixed effects. For each census block in the Savanna, I estimate the predicted soy expansion with and without the contracting effects. The counterfactual soy expansion assumes zero contracting effects. I find that the IV first-differences model predicts area expansion well in the Savanna, and I test the robustness of

the simulation results by using alternative definitions of contracting, alternative specifications with controls for the baseline characteristics, and various subsamples of farmers in the Savanna. The simulation results are presented in Table 8.

Table 8. Simulation of the Effect of Contracting on Soy Expansion in the Brazilian Savanna

| | Savanna | | |
|---|---|---|---|
| | Frontier | All locations with soy expansion | Soy Producers who expanded |
| Counterfactual simulation on soy expansion: | ( 1 ) | ( 2 ) | ( 3 ) |
| Contribution of contracting (%) | 84% | 49% | 37% |
| Sample: | | | |
| Soy production in 1996? | No | All | Yes |
| Soy Expansion? | All | Yes | Yes |
| Meso region fixed effects | Yes | Yes | Yes |

In the frontier, the introduction of the bundled contract explains 84% of total soy expansion. Restricting the sample to locations with soy expansion, the contribution of contracting is 49%. For the set of farmers who already produced soy in 1996, contracting contributes to 37% of total soy expansion. These estimates increase as I remove the restrictive mesoregion fixed effects; nevertheless, my preferred model uses the mesoregion fixed effects in combination with other baseline characteristics because they control for selection bias. The large contracting effects reported are therefore already conditional on the determinants of soy productivity across the Savanna region.

The large contribution of contracting to soy expansion in the frontier region further supports the value of the bundling mechanism of the new contract introduced in Brazil. The bundled contract was highly successful in the Savanna frontier because it simultaneously addressed the barriers to access to credit, output markets, and input markets with scale economies; the challenge of

putting together a complex new production system; and the need for specialized technical assistance to implement it.

**Contracting Effects on Agricultural Productivity and Land Use: IV Results**

The contribution of contracting is broader than expanding the agricultural frontier in Brazil. The "Miracle of the Cerrado" was unique for promoting economic development in a low-income region originally considered to be unsuitable for farming. I now exploit the rich census data to investigate the specific role of contracting in increasing agricultural productivity in the Savanna.

Table 9 reports the estimation results for Equation (17) with different agricultural outcomes. For each outcome, I report the results for frontier farmers as well as farmers who already produced soy in 1996. Columns (1) and (2) show the effect of contracting on soy area share. These results are consistent with the contracting effects estimated with area expansion as the outcome variable. In the frontier, contracting increases the soy share of total census block size by 13%. In the case of producers [column (2)], contracting increases soy share by close to 8%. These results are significantly higher than Bustos, Caprettini, and Ponticelli's (2016) estimates for technological change effects in Brazil. In the frontier, my estimates are about seven times larger, while for soy producers my estimates are four times larger. These differences reflect the distinct diffusion processes that occurred in Brazil from 1996 to 2006. Bustos, Caprettini, and Ponticelli's (2016) estimates capture the effect of GM diffusion in the South, while my estimates, using richer data and explicitly modeling the BNF diffusion, capture the much larger effect of the bundled contract in the Savanna frontier.

The effect of contracting on the total value of agricultural production was 200% in the Savanna and 65% in locations that previously produced soy, based on the estimates reported in columns (3) and (4). These estimates are actually much smaller than the effects implied by purely descriptive statistics (Figure 8), reflecting the influence of other drivers of agricultural value such as price increases. Nevertheless, contracting effects are still very significant statistically and economically. In columns (5) and (6), I report the estimates of the contracting effects on the expansion of total agricultural area, including grazing. I find that these estimates are not as robust as the ones previously reported, likely because the measurement of grazing area in the Savanna is not precise.

Table 9. IV Regressions of Soy Expansion: $\Delta Y_i = \delta_1 + \delta_2 d_{UF} + \beta_1 \Delta P_i + \beta_3 I_i + \beta_4 \Delta OC_i + \beta_5 \Delta X_i$

Contracting (I) is instrumented with the fitted values from Probit model for contracting choice.

| | Δ Soy Area Share | | Δ Log Output Value per ha | | Δ Agriculture Area Share | | Soy-Corn Production System | |
|---|---|---|---|---|---|---|---|---|
| | Frontier | Soy Producers who expanded | Frontier | Soy Producers who expanded | Frontier | Soy Producers who expanded | Frontier | Soy Producers who expanded |
| Variables | ( 1 ) | ( 2 ) | ( 3 ) | ( 4 ) | ( 5 ) | ( 6 ) | ( 7 ) | ( 8 ) |
| I: Contracting - IV | 0.131*** | 0.077** | 1.074** | 0.494* | 0.607** | 0.025 | 0.503*** | 0.286 |
| I: Contracting - OLS | 0.058*** | 0.059*** | 0.691*** | 0.310** | -0.001 | 0.001 | 0.431*** | 0.105 |
| *Exogenous variables:* | | | | | | | | |
| OC - Potential yield alternative crops | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Baseline Characteristics | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| State x Biome fixed effects | Yes | Yes | Yes | Yes | No | No | Yes | Yes |
| *Instruments in probit first stage:* | | | | | | | | |
| ΔA | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| N and pH | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Distance to Lime mine | Yes | Yes | Yes | Yes | No | No | Yes | Yes |
| Sample: | | | | | | | | |
| Soy production in 1996? | No | Yes | No | Yes | No | Yes | No | Yes |
| Soy Expansion? | All | Yes | All | Yes | All | Yes | All | Yes |
| Observations (census blocks) | 3,611 | 235 | 9,881 | 203 | 11,684 | 238 | 6,263 | 203 |
| F-Stat first stage | 18 | 16 | 44 | 14 | 9 | 2 | 41 | 23 |
| R2 OLS | 0.16 | 0.30 | 0.06 | 0.24 | 0.03 | 0.03 | 0.30 | 0.14 |

Notes: *** p<0.01, ** p<0.05, * p<0.1 . All standard errors clustered at Municipio level.
Contracting is instrumented with the fitted value of the Probit model for contracting choice. Opportunity cost variables are log of production value per hectare in 1985 and potential yield for alternative crops sugarcane, coffee, and cotton. Baseline characteristics are density and income per capita in 1985, and log of farm size in 1985. Additional controls are changes in prices of alternative crops and change in price volatility.

The Census micro dataset identifies managed grazing and natural grazing areas for each farm as well as natural vegetation areas, nevertheless, there is a high risk of misclassification as the definition of natural vegetation and natural grazing is very close.

Finally, I find significant and robust estimates of the effect of contracting in the adoption of complementary technologies. In the Savanna frontier, contracting increases by 50% the probability of adopting a multiple crop production system with corn and soy, resulting in further agriculture intensification in lands originally considered to be unsuitable for farming.

## 6. Conclusion

This paper investigates the role of a novel bundling mechanism for the diffusion of agricultural technologies in developing regions. The mechanism studied is a farmer-trader contract that combines output price guarantees, credit, a technological package of seeds, fertilizers, pesticides, and technical assistance. I provide empirical evidence that the introduction of this new type of contract in Brazil, following the implementation of market-oriented reforms, significantly contributed to the soy boom that transformed Brazil into the second largest producer and exporter of soybeans, and accelerated economic growth in low-income regions of the Brazilian Savana, which were originally considered unsuitable for farming.

In order to identify the effect of contracting on agricultural outcomes, I explore the timing of the introduction of the new bundled contract and cross sectional exogenous variation in crop suitability measures that drive the profitability of the contract-technology bundle in the Brazilian Savanna. I define the farmer choice of contracting and technology by combining rich farm-level data from two confidential agricultural census surveys, constructing a panel dataset that spans the period of the fastest soy expansion in Brazilian history. I find that the effect of the introduction of the new bundled contract explains most of the soy expansion in the frontier region of the Savanna and about half of the soy expansion in locations that already produced soybeans. I explored the rich census data to control for potential confounding effects, and I found that the empirical results are robust across different subsamples of farmers, different definitions of contracting, and alternative instruments for the potential profitability of contracting.

The empirical evidence presented in this paper supports a “bundling hypothesis” for the success of the new farmer-trader contract introduced in Brazil. The bundled contract was very effective, particularly in the Savanna frontier, because it addressed simultaneously multiple barriers that are common to technological adoption in developing countries: limited access to credit and output markets, inability to obtain cost-reducing economies of scale and to design a production systems efficient for low productivity soils, and lack of specialized technical assistance to implement advanced technological systems. Replicating the “Miracle of the Cerrado” in other developing regions might be challenging given the unique context of the Brazilian experience, but designing private bundled mechanisms adapted to specific technologies and locations could be an effective alternative for accelerating technological diffusion in low-income countries.

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