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Land institutions and supply chain configurations as determinants of soybean planted area and yields in Brazil

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ABSTRACT

Soybean production has become a significant force for economic development in Brazil. It has also received considerable attention from environmental and social non-governmental organizations as a driver of deforestation and land consolidation. While many researchers have examined the impacts of soybean production on human and environmental landscapes, there has been little investigation into the economic and institutional context of Brazilian soybean production or the relationship between soy yields and planted area. This study examines the influence of land tenure, land use policy, cooperatives, and credit access on soy production in Brazil. Using county level data we provide statistical evidence that soy planted area and yields are higher in regions where cooperative membership and credit levels are high, and cheap credit sources are more accessible. This result suggests that soybean production and profitability will increase as supply chain infrastructure improves in the Cerrado and Amazon biomes in Brazil. The yields of competing land uses, wheat, coffee, and cattle production and a complementary use, corn production, also help to determine the location of soybean planted area in Brazil. We do not find a significant relationship between land tenure and planted area or land tenure and yields. Soy yields decline as transportation costs increase, but planted area as a proportion of arable land is highest in some of the areas with very high transportation costs. In particular, counties located within Mato Grosso and counties within the Amazon biome have a larger proportion of their arable, legally available land planted in soy than counties outside of the biome. Finally, we provide evidence that soy yields are positively associated with planted area, implying that policies intending to spare land through yield improvements could actually lead to land expansion in the absence of strong land use regulations. While this study focuses on Brazil, the results underscore the importance of understanding how supply chains influence land use associated with cash crops in other countries.

Introduction

In recent decades, agricultural expansion and the growth of domestic and international markets for food commodities have become the most important drivers of large-scale land cover change in Brazil (Rudel, 2007; Defries et al., 2010). Soybean production has comprised a majority of the crop-based agricultural expansion, with soybean planted area increasing from roughly 1 million hectares (Mha) in 1970 to more than 23 Mha in 2010, second only to the United States (IBGE, 2006, 2010). In the Center West and Amazon regions, crop area expansion has resulted in the conversion of native savannas and forests and planted pastures to intensive agriculture (Brandão et al., 2006; Müller, 2003; Morton et al., 2006; Jepson, 2005; Rudorff et al., 2011; Macedo et al., 2012), and in some states, particularly Rondônia and Pará, soy production has also increased through the conversion and consolidation of smallholder lots (Brown et al., 2005; Fearnside, 2001; Steward, 2007). Additionally, soy expansion is hypothesized to displace cattle pasture into areas of native vegetation, particularly within the Amazon biome (Barona et al., 2010; Arima et al., 2011).

The rapid increase in soy production in Brazil over the last four decades was supported by government interventions to promote increased supply and increases in the global and domestic demand for soy derivatives. On the supply side, the factors affecting soybean expansion include major technological improvements in seeds in the 1970s, the introduction of credit subsidies and price supports in the 1980s, market deregulation and tariff reduction in the 1990s, and high global prices for soy and a competitive Real/US

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Dollar exchange rate in the late 1990s and 2000s (Spehar, 1995; Chaddad, 2006; Luna and Klein, 2006; Damico and Nassar, 2007; Richards et al., 2012). Soybean production was neither economically, nor biophysically viable on a commercial scale in the Center West region of Brazil until Brazil's Agricultural Research Corporation (EMBRAPA) developed new high-yielding cultivars, capable of tolerating the region's shorter day length and high aluminum and low calcium soils (Spehar, 1995). To encourage soy expansion in this region during the 1970s the government provided credit at negative real interest rates for land purchases and storage infrastructure, as well as low interest credit for operational expenses and price supports for soy, which allowed producers to migrate from the South of Brazil and exploit the vast agricultural potential of the Cerrado (Sousa and Busch, 1998; Damico and Nassar, 2007; Jepson et al., 2008).

On the demand side, an extreme El Niño event in 1972 greatly reduced the anchovy harvest of the coast of Peru, which led to a major increase in the demand for soy meal as a substitute for fish meal in global markets, and increased global soy prices (Warnken, 1999). Secondly, the United States responded to a local drought and high prices the following year by imposing an embargo on soy exports which further increased prices (Warnken, 1999). As a result, importing nations looked for additional countries, namely Brazil, to supply soy to world markets in the event of future US shortfalls. Due the supply side interventions, Brazil was able to seize the opportunity and became the second largest soy producer in the world by 1975 after producing only 1 million tons in 1969. Throughout the next three decades, urbanization and income growth in Brazil, China, and other emerging economies, coupled with Brazilian policies to stimulate the domestic consumption of soy products and poultry, led to a substantial increase in the global demand for soy as cooking oil and livestock feed (Sousa and Busch, 1998).

As a result of these programs, the Center West, which had virtually no soy production prior to 1980, now plants more soy than any other region in Brazil. Despite extensive study of the impacts of Brazilian soybean production as a driver of land cover change,[1] there has been little research on the economics of soybean production, in particular, the effect of supply chain configurations on local profits, the role of land institutions on land use, or the relationship between soybean yields and planted area. While past research largely focused on smallholders and cattle ranchers, soy production is very different from subsistence farming and ranching, requiring expensive machinery, skilled labor, and high levels of liquidity to finance yearly investments in soil correctives, defensives, and seeds (Brown et al., 2004, 2007). In order to predict how soybean production will develop in the dynamic agricultural regions of the Cerrado and Amazon ecosystems, it is necessary to understand better the determinants of spatial variations in soybean planted area and yields across all of Brazil.

The objective of this study is to assess the importance of biophysical, economic, and institutional conditions as determinant of regional variations in soybean planted area and yields, with a particular emphasis on the relationship between supply chain conditions and soy profits. To analyze the relative importance of each of these variables, we use von Thünen's spatial market model adjusted to include additional local variations in supply chain conditions. To examine the determinants of yields we use a bioeconomic yield model similar to that of Kaufmann and Snell (1997). We then use a two stage least squares model to analyze the influence of soy yields on planted area. This study adds to both the theoretical understanding of how supply chain configurations and land institutions influence land use and input usage, and the empirical understanding of soybean production patterns across all of Brazil. We find that supply chain configurations have a very strong relationship with soybean planted area and yields, but land institutions fail to predict land use patterns or yields. We also provide evidence that soybean yields and planted area in Brazil have had a positive relationship, as do yields and farm size, so land sparing is not likely to occur as a result of increasing soy yields if the global demand for soy is increasing or continues to be elastic.

Background

Planted area

To understand land use patterns we draw on agricultural location theory and the work of Johann Heinrich von Thünen, who hypothesized that in an area of spatially uniform fertility, the rent for a given parcel of land would be determined by its distance to the closest market (Jones et al., 1978). Over time, the basic transportation cost model developed by von Thünen has been adapted to include non-uniform biophysical conditions and variable input usage and used in numerous deforestation and agricultural expansion models (see Kellerman, 1989 for a detailed overview of the use of von Thünen models or Chomitz and Thomas, 2001; Mertens et al., 2002; Sills and Caviglia-Harris, 2009, or Walker et al., 2009 for applications in Brazil).

The von Thünen rent model we use differentiates between fixed and variable costs, acknowledges spatial differences in fertility, and allows rents to vary with input use and transportation costs to be non-linear.

$$R(U_{i,j}) = p_{i,j}y_{i,j}(x) - a_{i,j}x - t_{i,j}(m) - a^*_{i,j} \quad (1)$$

where $R(U_{i,j}(x))$ is the rent of a farm in location i in use j, $y(x)$ is the output of j at location i when x units of input are used, $p_{i,j}(y)$ is the market price of crop j in location i when y units of crop j are produced, a is the price per unit of input, $t_{i,j}(m)$ is the cost of transporting j m miles, and $a^*_{i,j}$ is the fixed cost of production for crop j in location i.

The resulting land use in a given location i is then modeled by the following discrete choice problem: if the present value of use j in a given area is greater than that of use k for an anticipated future time horizon h, then the profit maximizing land owner will convert their land to j. The present value (PV) of $U_{i,j}$ is given by:

$$PV(U_{i,j}) = \sum_h E\left[\frac{R(U_{i,j})}{\prod_p (1+r)^p}\right] - C_{i,j} \quad (2)$$

where E is the expectation, r is the interest rate, p is the number of years of ownership, and $C_{i,j}$ is the cost of conversion from the existing land cover to use j in location i. As present value is based on the expectation of rents, it incorporates the land user's understanding of the probability of multiple yield and price scenarios.

In the context of soybean production, which can be double cropped with corn, wheat, and other crops, the present value of converting the land to soybean production should also take into account the expected profits obtained from the production of a second crop within a given year. The present value of soy and its complements should then be compared to the expected profits of potential land use substitutes. From one year to the next, substitution options are limited to other annual crops for which the producer has technical expertise and suitable machinery. However, over multiple years, land cover can be changed, soil can be corrected, and ownership and/or operation can be transferred, increasing land use substitution possibilities. In Brazil, the main competitive land uses are cattle ranching and sugar production, whereas corn and wheat can be complements or substitutes

[1] See for example: Fearnside (2001), Brandão et al. (2006), Müller (2003), Brown et al. (2005), Morton et al. (2006), Jepson (2006a), Steward (2007), Arima et al. (2011), and Macedo et al. (2012).

depending on the crop variety and length of the growing season. In some regions, tree plantations, semi-permanent crop production (such as coffee and oranges), and agroforestry are also potential substitutes. This model also assumes that land cover is reversible, so if agricultural production becomes unprofitable, land will eventually revert back to natural vegetation (Chomitz and Gray, 1996).

Yields

Agricultural yields have been modeled in many different ways over the years, as documented in Kaufmann and Snell (1997) and Vera-Diaz et al. (2008). One set of yield models focuses exclusively on biophysical conditions and predicts plant growth and senescence as a response to climatic conditions. Another set of models focuses exclusively on economic factors and predict yields as a function of capital, labor, and land prices, where technology is embedded as the total factor productivity. However, focusing exclusively on either biophysical or economic factors ignores important variables, and a combination of the two sets of variables is needed (Kaufmann and Snell, 1997).

Rainfall, temperature, and solar radiation are all important biophysical factors that influence soybean yields in Brazil through their effect on evapotranspiration and soil moisture, while latitude determines the photoperiod (Ravelo and Decker, 1981; Garcia-Paredes et al., 2000; Sombroek, 2001; Chomitz and Thomas, 2001; Vera-Diaz et al., 2008; Schlenker and Roberts, 2009). Soil type and quality are also important determinants of agricultural yields through their effect on levels of nutrients, acidity, and heavy metals present in the soil (Chomitz and Thomas, 2001).

The economic factors influencing agricultural yields include crop and input prices, which may be influenced by transportation costs. For a profit-maximizing producer, the optimum usage of inputs is given by differentiating the rent equation with respect to x (the number of input units) and setting it equal to 0. This optimum is where the marginal revenue of an additional unit of x equals its marginal cost:

$$p_{i,j}y'_{i,j}(x) = a_{i,j} \quad (3)$$

Thus, the efficient level of inputs will decrease as prices of inputs increase or prices of outputs decrease. Since prices of outputs that are not consumed locally and prices of inputs that are not produced locally are a function of distance to markets, input usage is also a function of distance. In Brazil, soy production relies heavily on phosphorus, potassium, and lime inputs, due to the low natural fertility of the soils, high acidity and aluminum content. The costs of phosphorus and potassium are partially determined by transportation costs since they are largely imported (Brazilian Mining Institute, 2010). By contrast, all of Brazil's lime needs are met from production within the country (Brazilian Mining Institute, 2011). Therefore, fertilizer inputs should be lower in areas that have higher transportation costs to international ports, all else equal, but lime price and usage should be less influenced by transportation costs to ports. The biophysical and economic determinants of agricultural yields can be examined simultaneously using a multivariate regression model following Kaufmann and Snell (1997), Vera-Diaz et al. (2008), and Reidsma et al. (2009):

$$y(x) = f(\text{Biophysical Conditions}, \ \text{Economic Conditions}, \ \text{Technology}) \quad (4)$$

where economic conditions include local input and output prices and farm size. Yields can be related to farm size for a number of reasons: (1) returns to scale are not constant, (2) farm size influences prices paid per unit of input, (3) there is a dual market for labor (household and market) with different prices and productivity, or (4) there is a credit constraint related to farm size (Feder, 1985). For example, it is possible that smaller farms that have a higher ratio of family to hired labor will be able to apply more labor hours per hectare at a lower cost. However, it is also possible that larger farms might be able to afford newer, more efficient technologies that smaller farms would not have access to, such as precision agriculture. A majority of studies in developing countries found an inverse relationship between farm size and yields (Eastwood, 2010), but there is no evidence of this relationship in recent soy or corn production Brazil or the United States. In fact, Kaufmann and Snell (1997) found a positive relationship between farm size and yields in United States corn production. Helfand and Levine (2004) found a non-linear relationship between farm size and total factor productivity across multiple agricultural producer types in the Cerrado using data from the 1995/1996 agricultural census. They found that total factor productivity initially decreased with farm size, up to 1000–2000 ha, and then increased between 2000 ha and 20,000 ha, suggesting that economies of scale are only reached after a certain size.

Technology is embodied in the transformation function between inputs and output and may be affected by the size of the market. Seed manufacturers have an incentive to focus on developing and distributing higher yielding varieties in areas that have more farmers, i.e. a bigger market for their products. However, new seed varieties require many years of research and development before they can be adopted. Thus, current yields should be influenced by historical production.

Knowledge gaps

Despite the increasing importance of soybean expansion as a driver of land use change in Brazil, the theoretical land use and yield models outlined above have rarely been applied to the case of Brazilian soybean production (with the exceptions of Mann et al., 2010 and Vera-Diaz et al., 2008, who focused exclusively on soy production in the Legal Amazon for the 1995–1996 season). The Centerwest, Northeast, and North regions of Brazil have dynamic and rapidly developing agricultural systems that differ greatly from the South of Brazil, where soybeans were traditionally produced. Before applying these models to the case of Brazilian soy, two large theoretical gaps need to be addressed in the existing rent and yield models: how do *land institutions* and *supply chain configurations* influence local agricultural rents and yields?

Institutions are formal or informal rules that specify which actions or outcomes are forbidden, permitted, or required in a given context (Ostrom, 1986). Land institutions, in particular, are the rules that "mediate society's relationship with natural resources" and affect the ability of a land use agent to benefit from a given land use, through their influence on access (to technology, resources, information, etc.) (Ribot and Peluso, 2003; Jepson et al., 2010). A supply chain can be defined as the set of buyers and sellers that create linkages between a commodity's production, processing, and consumption. This chain includes the producers of the primary good, any intermediaries involved in the sourcing and trading of such goods, input vendors, financing institutions, and the consumers of the final product. Local variations in the *type and number* of producers, intermediaries, input vendors, financing organizations, and consumers, therefore, characterize what we call variations in the local *supply chain configuration*. Land institutions not only vary regionally in Brazil, but also locally in their interpretation and enforcement. Supply chain configurations also vary substantially at the local level. Both of these factors have the potential to cause local distortions in rents and the economically optimal usage of inputs.

Land institutions

Institutions relevant to soy production in Brazil include federal environmental laws, industry-led "market exclusion mechanisms"

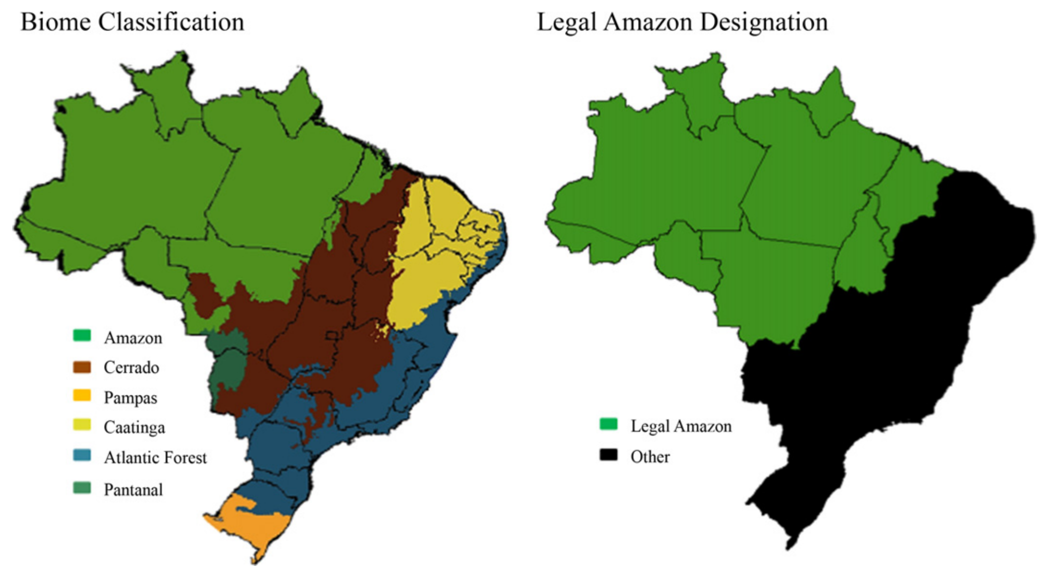

Fig. 1. Brazil classification system: difference between Amazon biome and legal Amazon.

(as described in Brannstrom et al., 2012), and land tenure conditions. The current Forest Code requires rural land users in the Amazon biome to conserve 80% of their property in a 'Legal Reserve', and landowners in the Cerrado to conserve 20% (Brannstrom et al., 2008, 2012). Producers in the 'Legal Amazon' portion of the Cerrado must conserve 35% of their property (Brannstrom et al., 2008, 2012; see Fig. 1). The initial text of the Forest Code in 1965 only required land owners to conserve vegetation classified as forest. Within the Amazon, this Legal Reserve was 50% of the property. In 1996, this reserve requirement was increased to 80% and vegetation characterized as savannah was included under the 35% reserve requirement (Alston and Mueller, 2007). Until recently, landowners in all parts of the country had to conserve steep slopes and the 30–500 m riparian areas adjacent to waterways (depending on the size of the waterway) as 'Permanent Protection Areas' (Brannstrom et al., 2008), but these protections are likely to be relaxed in the newest version of the Forest Code.[2] Producers in the Amazon region must also meet the requirements of the *Soybean Moratorium* to be able to sell to any of the major soy buyers. Companies that have agreed to the Soybean Moratorium will not purchase soy from producers who have planted soybean in areas deforested after 2006 (ABIOVE, 2010; Brannstrom et al., 2012).

These rules, if enforced, increase the transaction costs associated with production, decrease access to credit, and limit the overall scale of production, potentially preventing farmers from achieving economies of scale and an economically optimal farm size. For all these reasons, land within the Amazon biome should have lower potential rents, all else equal. As of 2006, 9.5% of Brazil's total soybean planted area (2.1 Mha) was located in the Amazon biome and 36% was located in the Cerrado (7.9 Mha) (IBGE, 2006).

Historically illegal clearings have been common, and enforcement of the Legal Reserve requirement has been poor (Fearnside, 2003; Alston and Mueller, 2007; Sparovek et al., 2010). In 2010, Sparovek et al. (2010) estimated that the Legal Reserve deficit in all of Brazil was 36 Mha (50% more than the total soybean planted area within the country). Within Mato Grosso, the largest soy producing state, Fearnside (2003) found that 95% of clearings between 2000 and 2001 were illegal. In contrast, there is some evidence that the present Soybean Moratorium is being enforced more successfully. Rudorff et al. (2011) used remote sensing and aerial surveys to analyze how much soy planting had occurred in areas that were deforested after 2006, and found that only 6300 ha, or 0.25% of the total deforestation in the areas they were monitoring, were planted in soybeans during the moratorium period.

Rules about land ownership and leasing (land tenure) can influence incentives to invest in soil conservation and correction if they influence a producer's ability to maintain control of their property in the long run. Where producers lease or own land without title they are expected to apply fewer soil correctives and plow their fields (instead of using no-till techniques that conserve soil), which could result in lower yields (Southgate, 1990; Alston et al., 1996, 1999; Barbier, 1997). Lack of secure ownership can also reduce rents (and therefore planted area) by influencing a producers' ability to obtain credit. If producers lack title to their land they can only use the potential value of their production as a guarantee on a bank loan, not the value of the land. As of 2006, the proportion of soy farms that reported a lack of land title in Brazil was very low, varying from 1% in the Southeast to 7% in the Centerwest (Table 1). The proportion of soy farms run by lessees was slightly higher, and varied between 1% in the Northeast to 17% and 18% in the Centerwest and Southeast, respectively (Table 1).

Table 1
Tenure arrangements in Brazil by region (1996–2006).

Tenure arrangements (1996 and 2006)						
Region	% of soy farmers					
	Own w/out title			Lease		
	1995	2006	Δ	1995	2006	Δ
South	9	18	9	13	13	0
Southeast	20	19	−1	28	21.5	−6.5
Centerwest	14	6.5	−7.5	23	17	−6
Northeast	35	11	−24	30.5	18	−12.5
North	8	10	2	9.5	11	1.5

Data: IBGE (1996, 2006).

[2] In May 2012, President Rouseff vetoed changes to the Forest Code that would provide amnesty to large landholders for prior illegal deforestation in the Amazon, but allowed changes to the law that will ease restrictions on the conversion of steep slopes, reduce Permanent Protection Areas around waterways to 5–100 m, and allow producers to use timber plantations as a reforestation mechanism. Full text on the bill and vetoes available at: www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12651.htm and www2.camara.gov.br/legin/fed/lei/2012/lei-12651-25-maio-2012-613076-veto-136200-pl.html.

Table 2
Supply chain configurations in Brazil by region (2006).

Supply chain configurations (2006)			
Region	% of soy farmers		
	Sold through coop	Sold to industry	Sold through intermediary
Brazil	65	12	16
South	69	9	15
Southeast	34	33	24
Centerwest	24	46	20
Northeast	2	61	13
North	6	34	31

Data: IBGE (2006).

Supply chain configurations

Ignoring local supply chain configurations in land use models assumes that the supply chain is fully competitive at every node (input vendors, credit providers, grain buyers, etc.) and that producers experience input and output prices that reflect the global (or national) price minus transportation costs. However, existing studies of crop production in Brazil, as well as the 2006 Agricultural census data, provide significant evidence that the structure and diversity of the soybean supply chain varies substantially by region (Sousa and Busch, 1998; Helfand and Levine, 2004; Jepson, 2006a; Jepson et al., 2010; Vera-Diaz et al., 2008; Brannstrom, 2009; Peine, 2009; Zanon and Saes, 2010). In particular, agricultural cooperatives, input vendors, and grain-traders serve different roles in areas where the supply chain is less diverse (and less competitive), and land and credit markets are not fully functioning, then they serve in areas with fully functioning and competitive land and credit markets.

Cooperatives help producers secure lower prices for inputs or higher prices for outputs through group purchases and sales or by enabling them to store their grain past the harvesting period and sell it when prices are higher (Sousa and Busch, 1998; Helfand and Levine, 2004; Zanon and Saes, 2010). In newer agricultural areas, such as the Centerwest, where cooperatives are less common, they may also help farmers obtain a land title (Jepson, 2006b; Jepson et al., 2010). In areas where there are no functioning cooperatives and insufficient on-farm storage, producers must sell their harvest directly to traders at the harvest time, which may not be when the market prices are highest (Peine, 2009). As of 2006, nearly 70% of producers in the South used cooperatives to sell their grain, while only 24% in the Centerwest and 2% in the Northeast used cooperatives to sell. In contrast, 46% producers in Centerwest and 61% of producers in the Northeast sold their soybean production directly to agribusiness industries (Table 2). While cooperatives might be less useful for extremely large farms that possess sufficient on-farm storage and the ability to negotiate better prices, cooperatives may still provide benefits through increased access to information about new technologies, better information about market prices, and access to forward markets for producers.

The Brazilian federal government provides agricultural credit through the National Rural Credit system, which is highly subsidized (Damico and Nassar, 2007). However, in areas where there are few federal banks, or where the supply of credit in these banks is explicitly limited or prohibited for soybean production as part of the *Federal Action Plan for the Prevention and Control of Deforestation in the Brazilian Amazon* (PPCDAM),[3] producers must rely on credit from traders and input venders, know as rural producer notes (CPRs). These contracts are known locally as *soja verde* contracts when producers trade a portion of their harvest in advance in return for credit, or *pacotes* when producers trade a portion of their harvest in return for a bundle of inputs (Fearnside, 2001; Damico and Nassar, 2007; Vera-Diaz et al., 2008). Interest rates can be very high in comparison to the low rates offered through government programs (up to 18% annualized for the 2009–2010 and 2010–2011 growing season compared to rates below 10% from government sources depending on the size of the farm) (Author, unpublished data). Since the higher interest rates on private versus public credit sources effectively increase the cost of production, it is expected that in regions where producers can't access the optimal amount of cheap government credit, their input usage, yields, rents, and planted area will all be lower.

Interactions between land institutions and supply chains

Supply chain actors can also influence how land institutions are enforced at the local level. In the absence of an effective centralized government monitoring system, compliance with the Forest Code and Soybean Moratorium depends on the extent to which decentralized, non-state actors, such as local branches of financial organizations or multinational grain trading companies, enforce land use rules when they finance or purchase from soy producers (Brannstrom et al., 2012). The *Protocolo Verde*, an agreement signed in 1995 by all of the federal banks, states that signatories will incorporate environmental impacts into their evaluation of projects, and prioritize activities that support "sustainable development" (Banco do Brasil, 1995). Thus, these organizations have committed to not finance producers or infrastructure projects that violate federal environmental regulations, and have the potential to aid enforcement of existing policies. Financial organizations and grain traders who are members of the Soybean Moratorium are also supposed to check whether producers have appeared on any embargo lists from the Brazilian Institute of Environment and Resources (IBAMA) or the Brazilian Association of Vegetable Oil Industries (ABIOVE) for violating Forest Code or Soybean Moratorium rules before they purchase grain from these farmers or provide them with credit (Cargill, 2006; Brasil, 2008).

Other non-state actors involved in the process of informal land institution creation and enforcement include environmental producers' groups and environmental NGOs such as the Nature Conservancy. These groups may act alone or in partnership with local governments to help bring producers into compliance with existing federal regulations, or create additional environmental standards for their members.[4] While these emerging governance mechanisms may appear as promising ways to reduce the environmental impact of agricultural production, there is little evidence that they have actually succeeded in enforcing existing regulations or the additional rules that they create (Brannstrom et al., 2012). Analysis of these governance mechanisms is greatly inhibited by a lack of access to data about the operations of these firms.

Expanded planted area and yield models

Planted area model

To address some of the knowledge gaps described above we revised the rent model and optimal input usage conditions

[3] In 2007, President Lula approved *Decree 6321/07*, an addendum to PPCDAM, which allowed the government to focus deforestation reduction actions in the 36 municipalities in the Amazon that accounted for 50% of total deforestation in the previous year (Lima, 2008). In an effort to improve monitoring of agricultural holdings, the producers in these counties were required to provide documentation of their properties, complete with GPS coordinates. If they failed to provide this information on time, they had their rural landholding certificates (CCIR) revoked, which effectively froze their access to credit (Environmental Defense Fund, 2009).

[4] See Brannstrom (2008) and Brannstrom et al. (2012) for examples related to soy production in Bahia and Mato Grosso.

to include variables that represent supply chains and institutions:

$$R(U_{i,j}(x)) = (1-f)_i[pc_{i,j} - pn_{i,j}]y_{i,j}(x) - x[ac + an(x)] - t(k) - a_o^* - a_r^* \quad (5)$$

where $R(U_{i,j}(x))$ is the rent of producing crop j in location i, f is the proportion of the land parcel that must be protected in native vegetation pursuant to the forest code in location i, $pc_{i,j}$ is the competitive farm gate price of j in location i, $pn_{i,j}$ is the cost of interest embedded in the output price when a soja verde or pacote contract is used and/or the difference price from selling j above or below the competitive market rate, $y_{i,j}(x)$ is the output of j given x units of input, ac_i is the competitive local market price of each unit in location i, an_i is the additional mark-up for interest charged on inputs, $af^*_{i,j}$ represents the non-institutional fixed costs of operation to produce crop j, and a_r is the transaction cost associated with proving compliance with all forest code regulations and obtaining an environmental license to produce and sell good crop j.

Using the discrete choice approach, every hectare that is currently planted in soybeans can be assumed to be a hectare where the present value of the expected future stream of soybean rents (or rents for soybeans double cropped with another crop) exceeds the value of any competitive land use. This expectation embeds an element of risk, as producers never know with certainty how prices, yields, and access to resources will change in the future. Given this framework, soybean planted area can be modeled as the outcome of all the factors that influence prices, yields, access, and risk: location (transportation costs), fertility (the biophysical component of yields), intensity (the amount of inputs used), and *relative* expected profits (of soy production in comparison to other land uses) (based on Kellerman, 1983). Intensity, in turn, is a function of land institutions (the effect of rules on access to resources and information) and supply chain configurations (profitability gains or losses associated with differences in marketing, purchasing, and credit options).

Yield model

Since land institutions and supply chain organizations affect input and output prices as well as access to certain inputs (namely land) they will affect the optimal use of inputs x, and resulting yields. To incorporate this dynamic we update the optimal (profit maximizing) input usage conditions and resulting yields in the following way:

$$[pc_{i,j} - pn_{i,j}]y'_{i,j}(x) = ac_{i,j} - an_{i,j} \quad (6)$$

where $y'_{i,j}(x)$ is the marginal output from an additional unit of input, and the rest of the variables are the same as Eq. (5). In this equation x may be restricted to a sub-optimal level due to credit access problems. Land tenure conditions can also affect yields directly by limiting the overall amount of credit producers can access and incentives to invest in soil quality.

Data and methods

Planted area model

To examine the relative importance of each one of the variables identified above for plant we developed the following estimating equation for planted area:

$$\text{Planted area} = \beta_0 + \beta_1 L + \beta_2 Y + \beta_3 I + \beta_4 S + \beta_5 C + u \quad (7)$$

where L represents location, Y is yield, I and S represent institutional and supply chain conditions, respectively, and C represents the yields of crops that are substitutes and/or complements. We then applied this model to county level data provided by the Brazilian Institute of Geography and Statistics. While this level of aggregation is a poor substitute for farm-level data, it offers a greater geographic coverage than local case studies. This form of aggregation is statistically appropriate as long as the county-level explanatory variables are uncorrelated with the aggregated errors in the observed land share devoted to soybean production (Miller and Plantinga, 1999). The measure we used for planted area was the area planted in soybeans in 2010 divided by the amount of arable land (measured in 2006) available in that county. Arable land was taken to be the sum of all land in a county that was not covered by physical structures, bodies of water, degraded, or otherwise inappropriate according to the Agricultural Census. This measure included forests, but not areas within forests that were designated as areas of permanent protection, as they would be unavailable for conversion. Because soybean planted area in 2010 was measured as a proportion of available arable land in each county it should reflect the relative profitability of soybean production in that county in comparison to other uses. Data on arable land, supply chain conditions, and land institutions came from the 2006 Agricultural Census, data on planted area and yields were taken from the 2006 to 2010 Municipal Agricultural Production surveys.[5] Unless otherwise noted, all data used in this study were derived from these two sources.

Location was represented using a categorical variable for the lowest transportation cost to the nearest port (from 0 to 275 US$/ton), based on the dataset developed by Vera-Diaz et al. (2009). We also included actual distance from São Paulo to account for distance to the major consumer market and any unmeasured factors related to colonization history that might influence soy area, as agricultural colonization has tended to progress from the southeast toward the northwest. For both of these variables we included squared terms to incorporate potential non-linearities in rents at very high costs and distances.

Yields were incorporated using a two-stage least squares approach, which included rainfall, temperature, latitude, and longitude as instruments for the five-year yield average between 2006 and 2010 (averaging the yields over a five year period reduces the impact of annual weather anomalies). Data on seasonal daily temperature and rainfall averages were collected by the Climate Research Unit of University of East Anglia (CRU-UEA) (New et al., 2002) and are available from the Brazilian Institute for Applied Economic Research (IPEA). This two-stage least squares approach was used to avoid possible endogeneity of average yields in prior years to current soy planted area in each region and because we were mainly interested in the total factor productivity differences between regions. Endogeneity leads to an over (or under) estimation of the causal importance of the variable in question (depending on the direction of the endogeneity) and may affect the calculation of the parameters on the other variables. We also included a variable for the average slope in each county, using the slope map developed by Sparovek et al. (2010), as slopes above 12% can prohibit the use of mechanized planting and harvest.

Our supply chain variables include the percentage of soy producers that sold their crop through agricultural cooperatives, the level of agricultural credit per unit of arable land in the county that was allocated specifically to cover the costs of production, the percent of annual crop producers that received any form of financing, and the percent of annual crop producers that received financing from government credit programs. All of these variables are from 2006 to

[5] All available at sidra.ibge.gov.br under the theme “agriculture”.

Table 3
Descriptive statistics for variables included in models.

Descriptive statistics of explanatory variables used in regressions ($n = 1180$)				
Group	Variable	Description	Mean	SD
Area	Soy planted area (%)	Soy planted area as a proportion of arable land (includes forest, excludes protected areas, degraded land, structures, water etc.) – 2010	23	28
Yield	Soy yield (MT)	Mean soy yield of farms w/in that county – 5 year average 2006–2010	2.54	0.40
Location	Transport cost ($/ton)	Cost of transporting a ton of soy one km via the lowest cost path to the nearest port – freight costs from 2006, land use and road network from 2000	52	29
	Distance São Paulo (km)	Distance from center of each county to São Paulo	1170	811
Biophysical conditions	Summer precip (mm)	Average monthly rainfall – January–March	188	51
	Winter precip (mm)	Average monthly rainfall – June–August	122	28
	Summer Av. temp (°C)	Average daily temperature – January–March	24.0	1.5
	Winter Av. temp (°C)	Average daily temperature – June–August	21.0	2.6
	Av annual temp (°C)	Average daily temperature – January–December	21.2	2.7
	Lat (dec. degree)	Latitude	−22	6
	Long (dec. degree)	Longitude	−51	3
Institutions	Own – no title (%)	% of soy establishments where the head of the establishment was the owner of the property but did not have definitive title – 2006	2	7
	Lease (%)	% of soy establishments where the head of the establishment was leasing the property – 2006	12	15
	Amazon (1, 0)	Whether or not a county fell within the legal Amazon boundary – 2006	3	17
Supply chain	Sold coop (%)	% of temporary crop establishments that were a member of a cooperative – 2006	16	19
	Credit level (million R$ (2000))	The amount of credit (Reais – 2000) received by temporary crop farms in 2004 per hectare of arable land in that county	168	299
	Use credit (%)	% of annual crop producing establishments in county received any form of financing – 2006	39	26
	Use gov credit (%)	% of establishments that received credit who obtained their credit through a government program – 2006	78	20
Substitutes	Cattle density (head/Ha)	Number of cattle per hectare of active planted pasture (not degraded, not natural) – 2006	2.5	1.9
	Sugar yield (MT/Ha)	Mean sugarcane yield of farms w/in that county – 2006	39	31
	Corn yield (MT/Ha)	Mean corn yield of farms w/in that county – 2006	1.05	0.79
	Cotton yield (MT/Ha)	Mean cotton yield of farms w/in that county – 2006	0.49	1.0
	Wheat yield (MT/Ha)	Mean wheat yield of farms w/in that county – 2006	3.5	1.6
	Coffee yield (MT/Ha)	Mean coffee yield of farms w/in that county – 2006	0.44	0.66
Spatial lag	Historical area (%)	Planted area in 2000 as a proportion of arable land	12	21
Farm size	Farm size (Ha)	Mean area planted in soy per farm, averaged across the country – 2006	133	170

Data: IBGE (2006).

reduce the potential endogeneity of supply chain conditions with soybean planted area in 2010.

The institutional variables included in the model were the proportion of soy farms in each county that were rented and the proportion of farms in each county that were owned without a definitive title. We included a dummy variable for whether a municipality is located in the Amazon biome to reflect the rules associated with the Forest Code. If any portion of the county fell within the Amazon biome the whole county is included in that category. We also included a dummy for Mato Grosso to test whether the counties in this state had a disproportionate effect on the dependent variables. To account for competitive land uses (the relative rent of soy in comparison to other uses) we included average corn, wheat, cotton, coffee, and sugar yields and the average stocking density of cattle.

Yield model

The yield estimation equation was written as:

$$\text{Yield} = \beta_0 + \beta_1 L + \beta_2 B + \beta_3 I + \beta_4 S + \beta_5 F + \beta_6 H + u \quad (8)$$

where L, I, and S are the same as above, B represents the biophysical conditions in the region (the same variables included the yield instrument equation above), F is the average farm size, and H is the historical planted area. The location, institution, and supply chain variables are the same as in the rent equation. The average farm size in each county was calculated using data on the distribution of farm establishments across multiple size categories:

$$\mu_{si} * d_{si} \quad (9)$$

where μ_{si} is the mean of size category s in county i and d_{si} is the proportion of soy establishments in each category.[6] To account for historical planted area in the region, we included the total planted area in 2000 as a proportion of arable land in each country averaged with its three nearest neighbors.

After the initial estimations we used the Moran I test to check for spatial autocorrelation in our residuals, which would lead to an underestimation of the error associated with our regression. The Moran I test indicated there was spatial autocorrelation in the estimation of both planted area and yields so we developed a spatial lag model for both of these estimations using the dependent variable for the three nearest neighbors:

$$Y_i = \rho W Y_k + \beta X_i + u_i \quad (10)$$

where W is the weighted average of the dependent variable for the k-nearest neighbors. X represents the independent variables

[6] The coefficient of variation on mean area was less than one in 50% of the counties, and less than two in 90%, indicating that planted areas were distributed close to the mean farm size in a majority of the counties. However, our farm size calculation is likely an underestimate for all counties, since the largest size category recorded in the census is “500 ha or more”.

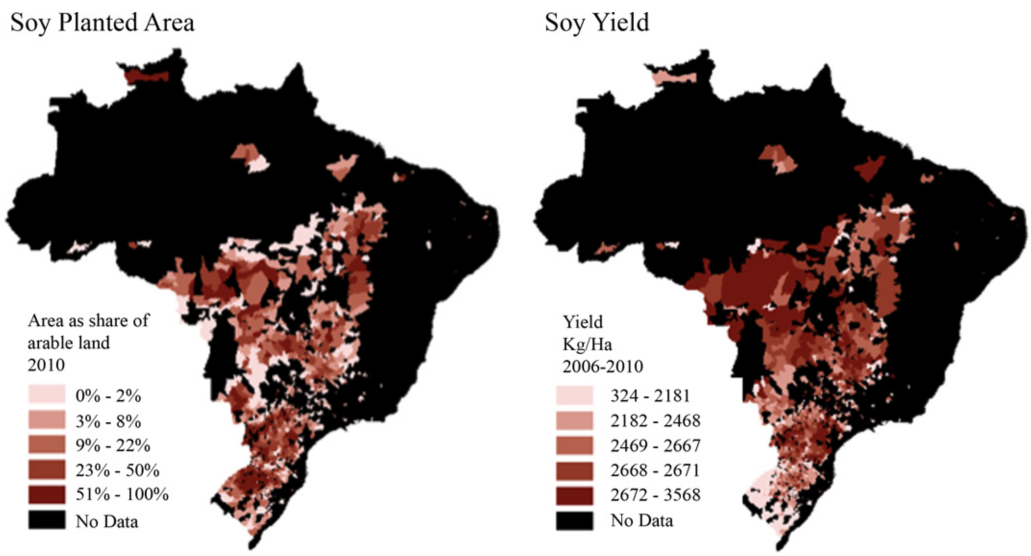

Fig. 2. Soy planted area as a proportion of arable non-protected land in 2010 and average soy yields between 2006 and 2010 in the counties included in our study.

defined above, and u is an error term. The estimate of the spatial lag parameter ρ represents the degree of spatial interdependence in the dependent variable – i.e., how much variation in the production in county i can be explained by the average production across its k nearest neighbors.

There were 1833 counties reporting their production of soybeans in the 2006 Agricultural Census, but only 1180 counties had data for all variables of interest. However, these 1180 counties accounted for more than 82% of all soy planted area that year. Table 3 provides descriptive statistics for the counties included in our analysis. Fig. 2 shows soy yields and soy planted area as a proportion of non-protect arable land in each county.

Results

The results of the planted area and yield regressions are shown in Tables 4 and 5. We also present the results of the first stage of our two stage least square model for yields in Table 6. Our models explained 64% of the spatial variation in planted area and 56% of the variation in yields when spatial lags were included and 58% of planted area and 41% of yields without the spatial lags. Inclusion of the spatial lags did not change the results substantially in either equation.

Transportation costs had a negative relationship to yields, except at very high costs where there was a small positive

Table 4
Estimation of soybean planted area.

Planted area model (n = 1188)	Log(SoyArea) – Model 1[a] Estimate (SE)	Log(SoyArea) – Model 2 Estimate (SE)	Log(SoyArea) – Model 3 Estimate (SE)
Intercept	−8.78*** (0.48)	−6.62*** (0.48)	−5.84*** (0.43)
TransCost	0.026*** (0.004)	0.022*** (0.004)	0.020*** (0.004)
TransCost²	−0.0001*** (0.0000)	−0.0001*** (0.0000)	−0.0001** (0.0000)
DistanceSãoPaulo	−0.17 (0.16)	−0.21 (0.15)	−0.23 (0.15)
DistanceSãoPaulo²	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Log(Yield)	–	–	2.18*** (0.19)
Log(YieldInstrument)	3.62*** (0.35)	2.99*** (0.34)	–
Log(Slope)	0.03** (0.01)	0.02* (0.01)	0.03** (0.01)
Amazon	0.51* (0.22)	0.45* (0.21)	0.50* (0.20)
%Own-Notitle	0.02 (0.45)	−0.20 (0.42)	−0.24 (0.41)
%Lease	−0.05 (0.22)	−0.19 (0.20)	−0.20 (0.20)
%SoldCoop	3.23*** (0.20)	2.45*** (0.20)	2.38*** (0.19)
Log(CredLevel)	0.55*** (0.03)	0.50*** (0.03)	0.50*** (0.03)
%UseCredit	0.00* (0.00)	0.00 (0.00)	0.00 (0.00)
%UseGovCredit	−0.19 (0.16)	−0.25 (0.15)	−0.24 (0.15)
Log(WheatYield)	−0.11* (0.05)	−0.10* (0.04)	−0.06 (0.04)
Log(CornYield)	0.02*** (0.00)	0.02***(0.00)	0.02***(0.00)
Log(CottonYield)	0.01 (0.00)	0.00 (0.00)	0.01 (0.00)
Log(SugarYield)	0.00 (0.00)	0.00 (0.00)	−0.01 (0.00)
Log(CattleYield)	−0.03 (0.07)	−0.12 (0.06)	−0.16** (0.06)
Log(CoffeeYield)	−0.03*** (0.01)	−0.01* (0.01)	−0.01 (0.01)
MTDummy	0.45* (0.20)	0.42* (0.18)	0.55** (0.18)
SpatialLag	–	0.35*** (0.03)	0.38*** (0.03)
R^2	0.58	0.64	0.65

Note: standard errors in parenthesis.
[a] Model 1: TSLS w/no spatial lag, Model 2: TSLS w/spatial area lag, Model 3: OLS w/spatial area lag.
* Significance at the 10% level.
** Significance at the 5% level.
*** Significance at the 1% level.

Table 5
Estimation of soybean yields with all variables.

Yield model ($n = 1188$)	Log (SoyYield) – Model 1[a] Estimate (SE)	Log (SoyYield) – Model 2 Estimate (SE)	Log (SoyYield) – Model 3 Estimate (SE)
Intercept	7.25*** (0.61)	3.78*** (0.55)	3.74*** (0.55)
TransCost	−0.003*** (0.0005)	−0.002*** (0.0004)	−0.002*** (0.000)
TransCost^2	0.000*** 0.000	0.000** (0.000)	0.000*** (0.000)
DistancetoSãoPaulo	0.00 (0.01)	0.00 (0.00)	0.00 (0.01)
DistancetoSãoPaulo^2	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Log(SummerPrecip.)	0.14*** (0.03)	0.03 (0.03)	0.02 (0.03)
Log(WinterPrecip)	−0.06*** (0.03)	−0.01 (0.02)	−0.01 (0.02)
Log(SummerTemp)	−1.68*** (0.22)	−1.10*** (0.19)	−1.10*** (0.19)
Log(WinterTemp)	−0.57 (0.35)	−0.16 (0.30)	−0.11 (0.30)
TempSquare	0.00*** (0.00)	0.00*** (0.00)	0.00*** (0.00)
Latitude	0.01 (0.01)	0.04** (0.01)	0.04*** (0.00)
Log(Slope)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
%Own-Nottitle	0.03 (0.06)	−0.01 (0.05)	−0.01 (0.05)
%Lease	0.02 (0.03)	−0.01 (0.02)	−0.01 (0.02)
%SoldCoop	0.15*** (0.03)	0.10*** (0.02)	0.10*** (0.02)
Log(CreditLevel)	0.01*** (0.00)	0.01*** (0.00)	0.01*** (0.00)
%UseCredit	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
%UseGovCredit	0.04* (0.02)	0.03* (0.02)	0.03* (0.02)
Log(FarmSize)	0.02*** (0.00)	0.02*** (0.00)	0.02*** (0.00)
FarmSize^2	0.00 (0.00)	0.00 (0.02)	0.00 (0.00)
HistoricalArea	0.02 (0.02)	0.00 (0.02)	
SpatialLag	–	0.61*** (0.03)	0.62*** (0.03)
R^2	0.41	0.56	0.56

Note: standard errors in parenthesis.
[a] Model 1: no spatial lag, Model 2: spatial yield lag and historical area, Model 3: spatial lag, no historical area.
* Significance at the 10% level.
** Significance at the 5% level.
*** Significance at the 1% level.

relationship. Conversely, transportation costs had a positive relationship with planted area, except at very high costs where there was a small negative relationship. However, overall, even large differences in transport costs explained very little of the differences in yields or planted area, while distance to São Paulo had no significant effect at all. Counties with \$100/ton higher transport costs had only 0.3% lower soy yields and a 2% higher soy planted area, all else equal.

Our land institution variables had very little effect on the location of soy planted area as a proportion of arable non-protected land or soy yields. All else equal, land tenure had no observable effect on planted area or yields and counties within the Amazon biome did not have lower planted areas. Instead Amazonian counties had a 0.5% higher planted area than counties that were not in the biome, while counties in Mato Grosso (within or outside the biome) had a 0.45% higher planted area than all other counties.

Table 6
Estimation of soybean yields with biophysical conditions only.

First stage estimation of yields ($n = 1188$)	Log(Average5YrYield) Estimate (SE)
Intercept	7.43*** (0.60)
Log(SummerPrecip)	0.17*** (0.03)
Log(WinterPrecip)	−0.10*** (0.02)
Log(SummerTemp)	−1.33*** (0.22)
Log(WinterTemp)	−1.05** (0.33)
TempSquare	0.00*** (0.00)
Latitude	0.03* (0.00)
Longitude	−0.01** (0.00)
R^2	0.34

Note: standard errors in parenthesis
* Significance at the 10% level.
** Significance at the 5% level.
*** Significance at the 1% level.

In contrast, supply chain configurations had a strong effect on both planted area and small, but significant effect on yields. The use of cooperatives to sell grain had a very strong positive relationship with soy planted area and a smaller, yet significant positive relationship with yields. A 1% increase in the number of producers using cooperatives to market soy was associated with nearly 2–3% larger soy area and 0.1% higher yield. The level of credit allocated to producers was also a significant positive determinant of both planted areas and yields. For a 1% increase in credit allocations there was a 0.5% higher planted area and a 0.01% higher yield. The proportion of farmers using any type of credit had a small positive effect on planted area, but no effect on yields. In contrast, use of government credit had a negative effect on planted area when the spatial lag was included and a very small positive effect on yields. For a 1% increase in the proportion of farmers using government credit there was a 0.25% decrease in planted area and a 0.03% increase in yields.

Biophysical factors were the most important factors influencing yields, confirming the results of Vera-Diaz et al. (2008). Precipitation levels during the summer months (December–February) had a positive effect on yields, while precipitation levels during the winter months had a negative effect on yields. Summer precipitation became insignificant in the spatial lag model. Higher summer temperatures had a very strong negative effect on yields. For a 1% increase in summer temperature there was a 1% decrease in yields. Farms at higher latitudes (further South with longer day lengths) had higher yields.

Farm size also had a small positive effect on yields. For a 1% increase in average farm size between counties there was a 0.02% increase in yields. Historical planted area in a county and its three nearest neighbors had a small positive effect on yields. For a 1% increase historical planted area there was a 0.02% increase in yields.

Soybean yields, instrumented through biophysical conditions, had a very strong positive effect on planted area. For a 1% difference in the yield instrument, there was a 2.5% increase in the amount of planted area (as a proportion of non-protected arable land). Wheat and coffee yields had a negative relationship with soybean planted area, but sugar and cotton yields had no effect. Cattle yields also had a negative relationship with planted area when the spatial lag was included. A 1% increase in wheat, coffee, and cattle yields was associated with a 0.10%, 0.12%, and 0.01% decrease in area, respectively. Corn yields had a positive relationship with soybean planted area. A 1% increase in corn yield was associated with a 0.02% increase in area.

Discussion

The fairly strong inverse relationship between yields and transportation costs suggests that many of the inputs to soy production are imported, making these inputs far more expensive further away from ports. Increases in the costs of inputs relative to the price offered for soy will reduce the economically optimal level of input, causing producers to use less of these inputs in areas of high transportation costs. However, there was a very small positive relationship between yields and the square of transportation costs, which is likely due to omitted variables. We do not include distance to lime mining operations since we did not have this information. The cost of lime may be cheaper in the regions with high costs to ports, since lime is mined in many areas of central Brazil. Another possibility is that labor costs are lower in regions that have high transportation costs as these regions are typically far away from urban areas, and may have few off-farm employment options.

The finding that soybean planted area had a positive relationship with higher transportation costs, except at very high costs, contradicts standard von Thünen theory. One explanation is that initial land prices were not accounted for in the model. It is likely that land prices were initially much lower in counties very far from export ports, encouraging soybean farmers to expand in these areas through private colonization firms as agricultural land became scarce in the South of Brazil. Evidence of this process is well documented in the work of Jepson (2006a,b), which shows how private colonization companies and cooperatives helped producers establish farms in Mato Grosso, build roads, and overcome high transportation costs to markets.

The fact that the Amazon region had a slightly higher proportion of their arable, non-protected land planted in soy negates our hypothesis that Forest Code and Soybean Moratorium regulations would decrease incentives to expand soy in the Amazon biome by increasing transaction costs, decreasing access to credit, and limiting the scale of production. One explanation might be that much of the soy expansion in these regions took place prior to the 1996 Forest Code revisions and the more recent Soybean Moratorium. Another possibility is that the disadvantages of strict institutions are outweighed by other advantages of expanding into the Amazon, such as lower initial land prices and the potential to capture land title through land conversion, as suggested in Bowman et al. (2012) with respect to cattle expansion. Secondly, the size of the sample within the Amazon was fairly small (52 counties) and six counties in Mato Grosso highly influenced the result including: Diamantino, Querencia, São Jose do Rio Campo, Sinop, Sorriso, and Tapurah, which all had more than 50% of their arable non-protected land planted in soy. Some of these counties are only partially in the biome, which also might have skewed the result.

The insignificant association between land ownership without title and both planted area and yields could be attributed to the fact that land tenure problems are not common enough among soybean producers to make a significant impact in overall expansion patterns and yields. The average proportion of soy producers that did not have title in our sample was only 2%. Thus, while land title problems may explain differences in land use between producers within the same county, they do not appear to be a direct driver of regional patterns of land use change. Also, the most important effect of land tenure insecurity may be reduced access to credit, which we controlled for and found to be a significant determinant of planted area and yields.

The insignificant association between land leasing and yields might be explained by the tendency of soy producers in Brazil make 5–10 year leasing contracts. Thus if the renter reduced their inputs substantially in the first years of their contract they could suffer from substantially lower yields in the last years of their contract (the effect is fairly immediate, rather than long term). Also, where producers are renting previously uncorrected land, such as pasture, the landlord often compensates the tenant for their contribution to improving the soil quality by offering initial lower leasing prices.

Our results strongly support our hypothesis that the organization and diversity of local supply chains has a strong influence on regional variations in planted area and yield. In particular, the use of cooperatives had a very powerful positive effect on planted area. One caveat of this result is that cooperative usage may be partly endogenous to planted area if the use of cooperatives to sell grains increases *as a result of* higher levels of soybean production. However, cooperative participation would not continue in the long run unless it was economically benefiting the producers who participated. While cooperatives might serve an important role in securing lower input costs for producers, the most important role of cooperatives may be that they allow producers to avoid depressions in local soy prices during peak harvesting periods by storing a portion of the harvest. They also produce economies of scale with grain buyers, who call the cooperatives when prices are high to see if any of their members want to sell at that time.

The finding that credit levels and the overall use of credit by producers had a positive effect on planted area, but a weaker effect on yields, suggests that abundant credit allows producers to increase land as a factor of production, but does not cause producers to focus on yield improvement in lieu of area expansion. The negative relationship between government credit and planted area, combined with the positive relationship between government credit and yields suggests that subsidized government credit that is specifically targeted for input purchases might provide incentives for producers to invest in yields rather than area expansion.

The positive relationship between farm size and yields suggests that economies of scale do occur in mechanized soy production. These economies of scale may include reduced input costs, increased access to more technologically advanced machinery, and access to better agronomists. Thus, while the consolidation of soy farms in the hands of fewer producers maybe socially undesirable from an equity perspective, it also has the potential to improve the efficiency of soybean farming in Brazil.

Finally, this study also sheds light on the debate about whether soybean yield improvements can spare land in the Amazon and Cerrado. Our results showed that counties with higher yields had *higher* levels of soybean planted area given the amount of non-protected arable land in their county. Since yields were instrumented through biophysical conditions, which are essentially free (provided by nature), our finding suggests that counties that have total factor productivity advantages over other counties will experience higher levels of land use conversion for soybean production. Increasing soybean yields over time in a given plot of land through technological improvements (such as better cultivars) will only increase the rents from soy on that plot, and increase producer incentives to expand their production over time, provided that the demand for soy is elastic (as discussed extensively in Angelsen and Kaimowitz, 2001, 2010; Kaimowitz and Smith, 2001). In contrast, a reduction in total factor productivity from climate change could greatly decrease soy rents and reduce incentives for soy producers to expand their production over time. In particular, the fact that summer temperature had a negative effect on yields (while summer precipitation had a positive effect) suggests that yields could be reduced substantially if the main soy cultivating regions in Brazil become hotter and drier during the summer.

Our data reflects one snapshot in time, and spatial trends revealed by the study should not be interpreted as a proxy for time effects. Furthermore, results at the county level do not explain differences in behavior between farmers within a county. Nevertheless, our analysis identifies larger spatial trends in soybean production systems that are critical for better understanding soybean expansion and intensification.

Conclusion

In the past fifty years the demand for soy increased from 26 to 260 million tons and will continue to grow in the future as demand for cooking oil, livestock feed, and biodiesel increase with income growth and changing dietary preferences in emerging economies (FAO, 2012). China in particular has consistently imported over 50% of all raw soybeans traded in international markets over the past 8 years to feed their growing livestock sector and cooking oil needs (Trostle, 2008). This demand has been met, in part, by massive soy area expansion in Brazil and Argentina, in addition to yield improvements.

While recent studies have emphasized the *intertemporal impacts* of soy area expansion, in particular, the relationship between soy area, cattle pasture area, and land cover, our study analyzed the causes of *spatial variations* in soy area expansion across Brazil. We found that local variations in supply chain conditions played a very important role in determining spatial differences in soybean yields and planted area, but land tenure conditions had little effect. We also found that transportation costs had a positive relationship with planted area, except at very high costs, challenging conventional theory that land use decreases monotonically with transportation costs. Thus, future spatial models of soybean area and yields should account for regional differences in supply chain configurations, total factor productivity, and initial land values, in addition to transportation costs.

Our study also showed that there is a strong positive relationship between soy yields and planted area, implying that policies intending to spare land through technological yield improvements could actually lead to land expansion in the absence of strong land use regulations. Moreover, the strong relationship between summer temperatures and precipitation and yields suggests that future climate variability marked by temperature and precipitation extremes, in addition to increased mean temperatures with global warming, could reduce yields and cause a retraction in soy planted area.

It remains unclear, however, why supply chains develop differently across new regions of soybean production, how supply chain actors affect each other, and how supply chain conditions interact with land institutions and transportation costs. Are the locations of supply chain clusters driven mainly by the scale of production in a region and logistical advantages, or do government policies, specifically land use regulations, drive agribusiness investment and concentration? Addressing these questions in future studies will help us understand how soy supply chains will continue to develop in Brazil in the future, and what spillover effects land institutions might have on soybean profitability through interactions with supply chains.

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