MARCELO DIAS PAES FERREIRA

CLIMATE CHANGE, FARM SIZE AND LAND USE IN BRAZILIAN LEGAL AMAZON

Tese apresentada à Universidade Federal de Viçosa como parte das exigências do Programa de Pós-Graduação em Economia Aplicada para obtenção do título de Doctor Scientiae.

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BIOGRAPHY

MARCELO DIAS PAES FERREIRA, son of Ione Maria Dias Paes and José Hélcio Ferreira, was born in Ervália, Minas Gerais, Brazil, in April 15th, 1986.

He started his undergraduate studies at *Universidade Federal de Viçosa* in March of 2004, receiving his B.A. in Agribusiness Management in July of 2009.

He started the M.Sc. in Applied Economics in August of 2009 and defended his dissertation titled "*Impactos dos Preços das Commodities e das Políticas Governamentais sobre o Desmatamento na Amazônia Legal*" in November 7th, 2011.

He started the D.Sc. in Applied Economics in March of 2012 and defended his thesis titled Climate Change, Farm Size and Land Use in Brazilian Legal Amazon in July 17th, 2015.

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ABSTRACT

FERREIRA, Marcelo Dias Paes Ferreira, D.Sc., Universidade Federal de Viçosa, July, 2015. **Climate change, farm size and land use in Brazilian Legal Amazon.** Adviser: José Gustavo Féres.

Brazilian Legal Amazon is strategic to Brazilian environmental and social achievements and land use plays an important role in this context. This study aimed to assess how climate change and farm size would affect the land use pattern in this region. We developed two chapters to address these issues: Climate Change, Climate Risk and Land Use in Brazilian Legal Amazon and Farm Size and Land Use Efficiency in Brazilian Legal Amazon. In the first chapter, we set up a risk-averse land use model. Results pointed out that the amount of rainfall, inter-annual temperature variance and inter-annual rainfall variance are associated to land use allocation in Brazilian Legal Amazon. There is evidence that farmers are risk-averse and the establishment of pasture is positively associated to rainfall risk. Our climate change simulations indicate that there will be re-allocation of land from forest and crops to pasture. Depending on the increase in climate variability and time horizon, deforestation ratios range between 10% to 16% of total forest areas. In the second chapter, we measure land use efficiency and technical efficiency by Stochastic Frontier Analysis. We found that farm size is negatively associated to the productivity measures. Therefore, larger farms are less productive and waste more land than smaller farms.

RESUMO

FERREIRA, Marcelo Dias Paes Ferreira, D.Sc., Universidade Federal de Viçosa, julho de 2015. **Mudanças climáticas, tamanho das propriedades e uso da terra na Amazônia Legal brasileira.** Orientador: José Gustavo Féres.

A Amazônia Legal é estratégica para os indicadores ambientais e sociais brasileiros e o padrão do uso da terra nessa região influencia tais indicadores. Nesse sentido, este trabalho buscou avaliar como as mudanças climáticas e o tamanho das propriedades afetaram o padrão do uso do solo nessa região. Para responder esses questionamentos, foram desenvolvidos dois capítulos: *Climate Change, Climate Risk and Land Use in Brazilian Legal Amazon* e *Farm Size and Land Use Efficiency in Brazilian Legal Amazon*. No primeiro capítulo foi desenvolvido um modelo de uso da terra incorporando aversão ao risco. Os resultados indicam que a quantidade de chuvas, variância interanual da temperatura e variância interanual das chuvas afetam a decisão de uso da terra na Amazônia Legal. Constatou-se que há evidência de aversão ao risco por parte dos produtores rurais na região e que o estabelecimento de pastagens está associado positivamente com risco pluviométrico. Simulações realizadas a partir de projeções climáticas indicam que a estratégia de adaptação por parte dos produtores é a conversão de áreas de lavouras e florestas em pastagens. Dependendo do aumento da variabilidade climática e do horizonte de tempo, a taxa de desmatamento varia de 10% a 16% da área total de florestas nas propriedades rurais. No segundo capítulo, foi medida a eficiência do uso da terra e a eficiência técnica por meio da Análise de Fronteira Estocástica (*Stochastic Frontier Analysis*). Foi verificado que o tamanho das

propriedades na Amazônia Legal está negativamente associado às medidas de produtividade. Assim, propriedades maiores apresentam menor produção e desperdiçam mais terra do que propriedades menores.

1. Introduction

Land use is an important environmental and social attribute. Nowadays, there is a great concern regarding Greenhouse Gases (GHG) emissions and biodiversity losses due conversion of natural vegetation into agricultural land. The process of land concentration has also drawn the attention of policymakers around the world, urging a call for a more equitable agrarian organization. In this sense, Brazilian Legal Amazon (BLA) is strategic to Brazilian environmental and social achievements, since the region historically has been regarded as the main world agriculture frontier (Hecht 1985, 1993)[1]. Although deforestation in BLA has decreased during the last decade[2], this region has presented high deforestation rates over the time. The average deforestation rate was 15,000 km^2 over the last two decades (INPE 2015). Therefore, deforestation and land use patterns in BLA still remains a challenging issue for policymakers.

Although the role of deforestation in GHG emissions has been extensively studied, there is a lack of literature regarding the impact of climate change on land use in BLA. Agricultural production is a source of land use change and the change on climate pattern could force farmers to adapt. For instance, areas with higher precipitation are not suitable to cattle production due to incidence of parasites and insects (Chomitz and Thomas 2003; Sombroek 2001). Furthermore, the higher the

[1] BLA is a socio-economic region within Brazil created in 1950s for political purposes. It spans for nine states, covers 61% of Brazilian territory and is slight smaller than Europe. The 4 million km^2 of Brazilian Amazon lies within the 5.2 million km^2 of BLA, the remaining is mostly cerrado biome (Homma 2008; SUDAM 2010).

[2] Command and control policies, monitoring systems, and supply chain interventions have reduced deforestation to less than 7,000 km^2 per year since 2010 (E. Y. Arima et al. 2014; J. Assunção, Gandour, and Rocha 2015; Ferreira and Coelho 2015; Hargrave and Kis-Katos 2013; Nepstad et al. 2014).

precipitation, more difficult it becomes to adopt mechanizing agriculture and slash and burn practices (E. Y. Arima et al. 2011). Thus, a lesser rainfall incidence could benefit cattle production, fostering conversion of forest into pastures.

Land concentration in BLA could also present environmental impacts in the future, as land is historically poorly distributed in Brazil and BLA (see Table A1 in appendix). About 60% of farmland belongs to establishments with more than 1,000 hectares in 2006 and these large farms represent 2.4% of the number of farms. In turn, establishments smaller than 10 hectares cover 1.33% of total farmland and corresponded to 35.4% of the number of farms. Land also has concentrated over the time in BLA. Establishments smaller than 10 hectares were 55.6% of the total and covered 1.97% of BLA farmland in mid-1980s (IBGE 2014).

This land concentration trend could be associated to a less efficient use of deforested land. In his seminal paper for Indian agriculture, Sen (1962) pointed out that agricultural productivity presents an inverse relationship with farm size. After these early findings, several studies verified this stylized fact for developing world (e.g. J. J. Assunção and Braido 2007; Bardhan 1973; Barrett, Bellemare, and Hou 2010; Bhalla and Roy 1988; Carter 1984; Cornia 1985; Newell, Pandya, and Symons 1997). If this inverse relationship holds to BLA, the land concentration process could lead to a worse utilization of deforested land. However, some studies for Brazilian agriculture have ruled out the inverse relationship hypothesis between farm size and productivity (Freitas 2014; Helfand and Levine 2004; Oliveira 2013).

1.1.Problem and Importance

As land use in BLA is a substantial Brazilian environmental indicator, a more rational use of land should guide policies applied to this region. Therefore, there is a need to assess the evolution of land use in the light of climate change and land concentration. In this study, we will focus on the relation between climate change and land use pattern as well as the issue of farm size and land productivity.

Understanding how land use patterns could respond to climate change is of paramount importance for policy formulation to BLA, as these changes could present environmental, economic and institutional consequences. For instance, annual crops stock 2.7 times more carbon than pasture in western BLA (Fujisaka et al. 1998). Secondary forest recover faster in abandoned cropland than in abandoned pasture (Fearnside 1996; Fearnside and Guimarães 1996). Pasture for cattle requires more land, demands less workforce and is less economically productive (Andersen, Granger, and Reis 1997). Forest conversion into pasture in BLA is a strategy to ensure property rights and foster land speculation (Fearnside 2001; Pacheco 2009). Furthermore, there is a need for policies of land ordering to prevent the impacts of climate change related to deforestation.

Despite the importance of comprehensive assessments of land use pattern, most of the literature have focused on the sources of deforestation in BLA[3]. Few studies have investigated how deforested land could be allocated in competitive uses

[3] These studies could be divided in: general analysis (Andersen 1996; A. S. P. Pfaff 1999); rural development and institutional perspectives (Araujo et al. 2009; Caldas et al. 2003; Marchand 2012; Perz and Walker 2002; Sant'Anna and Young 2010; Walker, Moran, and Anselin 2000); price and market-oriented analysis (Andrade de Sá, Palmer, and di Falco 2013; E. Y. Arima et al. 2007; Mann et al. 2010; Mertens et al. 2002; Verburg et al. 2014); the role of the transport infrastructure (Barber et al. 2014; A. Pfaff et al. 2007; Weinhold and Reis 2008); assessment of command and control policies (J. Assunção, Gandour, and Rocha 2015; E. Y. Arima et al. 2014; Ferreira and Coelho 2015; Hargrave and Kis-Katos 2013; Nepstad et al. 2014); the impact of climate variables (Chomitz and Thomas 2003; Sombroek 2001); and the role political cycles (Rodrigues-Filho et al. 2015).

(Andersen, Granger, and Reis 1997; E. Y. Arima et al. 2011; Mendonça, Loureiro, and Sachsida 2012; Weinhold 1999), and they do not analyze the mechanisms underlying land use conversion. Thus, the above-mentioned approaches do not provide an adequate framework for analyzing farmers' adaptive strategies.

We propose an approach that differs from the current literature for BLA. First, we assess the impact of climate change by specifying a land use structural model[4], which allow us to expose the mechanisms of farmers' adaptation to climate change. Second, we also model risk-aversion related to exogenous climate variability. This is a novelty in land use modeling and has relevant environmental policies implications. For instance, Knoke et al. (2011) found that the cost of avoided emissions from deforestation are greatly different when agents are neutral or risk-averse. In our case, accounting for risk-aversion would present an important policy insight. We argue that the fact that cattle (a low yield activity) is the dominant land use in BLA is related to agents' risk-averse behavior. Therefore, farmers would be willing to engage in a less expected profitable activity, like cattle, if it is also less risky.

The inverse relationship between farm size and agricultural productivity also presents environmental policy implications. The main explanations for this relationship relies on labor effectiveness differences associated to dual labor market (Sen 1962; Sen 1966), risk-aversion (Barrett 1996; Srinivasan 1972), and moral hazard

[4] Our land use structural model is based on studies for other contexts (Arnade and Kelch 2007; Chambers and Just 1989; Coyle 1993a; Coyle 1993b; Fezzi and Bateman 2011; Fezzi et al. 2014; Gorddard 2013; Heres, Ortiz, and Markandya 2013; Kaminski, Kan, and Fleischer 2012; Lacroix and Thomas 2011; Moore, Gollehon, and Carey 1994; Moore and Negri 1992).

and supervision of labor (Bardhan 1973; Eswaran and Kotwal 1986; Feder 1985)[5]. These three explanations predict that farm size is negatively associated to productivity.

One could measure agricultural productivity by some efficiency indicator, representing total factor productivity (Helfand and Levine 2004). In this sense, technical inefficiency is a measure of resource waste related to the best-observed practice. Thus, more efficient farms would spare land, reducing the need for deforestation. In the BLA context, Otsuki, Hardie, and Reis (2002) found that well-defined property rights enhance economic efficiency, reducing the need for more deforestation. Helfand and Levine (2004) identified a "U" shaped relationship between farm size and technical efficiency in Brazilian mid-west. Thus, both larger and smaller farms are more efficient than median farms. Finally, Marchand (2012) assess the relationship between technical efficiency and deforestation in BLA. He found a "U" shaped relationship, where less and more efficient farms deforest more than average efficient farms.

Nonetheless, all of the above-mentioned studies have used a misleading measure to gauge the surplus of land used in agricultural production. The recurrent technical efficiency approach capture the misuse of all inputs and do not provide a single measure of land waste. The surplus of land is associated to the amount of avoided deforestation without compromise the actual agricultural production. Therefore, there is a need of a land efficiency indicator based on an input-specific technical efficiency to gauge land surplus. Reinhard, Lovell, and Thijssen (1999) provide an approach to measure input waste associated to an environmental attribute. This approach consists in analyze the ratio of the minimum possible use of a single

[5] See section 3.2. "The Relationship between Farm Size and Productivity" for further details on theoretical explanations of the inverse relationship between farm size and land productivity.

input between the best observable use of this factor, keeping constant the level of output and other inputs. We used this latter approach in order to measure land waste in BLA.

1.2. Hypotheses

- Pasture establishments are a hedge strategy to climate risk in Brazilian Legal Amazon;
- Climate change will increase land allocation in pastures and decrease land allocation in crops and forest in Brazilian Legal Amazon;
- There is an inverse relationship between farm size and productivity across Brazilian Legal Amazon.

1.3. Objectives

1.3.1. General Objective

- Assess land use pattern in Brazilian Legal Amazon, highlighting the role of climate change and farm size.

1.3.2. Specific Objectives

- Clarify farmers' decision of land use allocation;
- Identify the impacts of climate change on land use;
- Analyze the relationship between farm size with technical efficiency and land use efficiency.

We developed two chapters to achieve the specific objectives. The first two specific objectives are addressed in the chapter "Climate Change, Climate Risk and

Land Use in Brazilian Legal Amazon”. The chapter “Farm Size and Land Use Efficiency in Brazilian Legal Amazon” addresses the third specific objective.

2. Climate Change, Climate Risk and Land Use in Brazilian Legal Amazon

2.1.Introduction

Global climate change will likely have adverse consequences on agriculture. In the near future, rural areas will probably face impacts on water availability and supply, food security, and agricultural incomes (IPCC 2014). Climate change will also modify climate variability pattern. For instance, more extremes events are likely to occur such as droughts and heat waves (IPCC 2014).

Brazil provides a compelling setting for studying the effects of climate change on agriculture. First, Brazil is currently the fourth worldwide producer and exporter of agricultural goods (FAO 2015). Second, the country has experienced a boom in agricultural sector since 1970s. Agricultural expansion has triggered the conversion of vegetation into agricultural use, especially in Amazon and cerrado biomes. In fact, Brazilian Legal Amazon (BLA)[6] is regarded as the main agricultural frontier worldwide. Although deforestation in BLA has decreased during the last decade, it still presents high values. For instance, average deforestation rate has been 15,000 km^2 per year over the last two decades (INPE 2015). Recently, command and control policies, monitoring systems, and supply chain interventions have reduced deforestation to less than 7,000 km2 per year since 2010 (J. Assunção, Gandour, and Rocha 2015; Hargrave and Kis-Katos 2013; Ferreira and Coelho 2015; Nepstad et al. 2014; Richards, Walker, and Arima 2014). Third, Brazil was the sixth GHG emitter

[6] BLA is a socio-economic region within Brazil created in 1950s for political purposes. It spans for nine states, covers 61% of Brazilian territory and is slight smaller than Europe. The 4 million km^2 of Brazilian Amazon lies within the 5.2 million km^2 of Brazilian Legal Amazon. The remaining is mostly cerrado biome (Homma 2008; SUDAM 2010).

country in 2011, accounting for 3.1% of world emissions (WRI 2015). Agricultural and land use change is identified as the main source of GHG emissions in Brazil[7]. BLA has substantially contributed to Agriculture, Forestry and other Land Use (AFOLU) emissions, since it represents Brazil's main agricultural frontier. Therefore, what happens in BLA regarding land use is of global concern.

Several studies have analyzed the role of land use change in BLA on GHG emission mitigation (e.g. Cohn et al. 2014; Santilli et al. 2005; Stickler et al. 2009; Strassburg et al. 2009). However, few studies have been devoted to assess the inverse relation, the effect of climate change on land use patterns in BLA. Climate change is likely to influence land use patterns in BLA, since farmers would adapt to this phenomenon. Changes in temperature and rainfall variability could also lead to changes on land use decisions due farmers' risk-aversion. Climate change can induce more forest conversion into agricultural land. This would increase GHG emission related to agriculture. Climate change may also induce conversion of cropland into pasture. All these changes present important environmental and economic consequences. Therefore, there is a need to assess these potential impacts.

There are three main approaches to measure impacts of climate change on agriculture: Agronomic/Production Function; Ricardian/Hedonic; and Computable General Equilibrium (CGE) models[8] (Fezzi et al. 2014; Schlenker, Hanemann, and

[7] Agriculture, forestry and other land use (AFOLU) accounted for 24% of worldwide GHG emissions in 2010 (IPCC 2014). AFOLU GHG emissions in Brazil accounted for 57% for the same year (BRASIL 2013).

[8] See Adams (1989) and Adams et al. (1995) as examples of Agronomic/Production Function approach; Mendelsohn, Nordhaus, and Shaw (1994), Schlenker, Hanemann, and Fisher (2005, 2006), and Deschênes and Greenstone (2007) as examples of Ricardian/Hedonic approach; and Hertel, Burke, and Lobell (2010), Hertel (2011), and Ferreira Filho and Moraes (2015) as examples of CGE models.

Fisher 2006). The Agronomic approach evaluates the direct impact of climate change on yields. However, this approach implicitly relies on the so-called "dumb farmer" hypothesis, since it does not consider a broad range of adaptive strategies. Failing to address adaptation strategies tends to overestimate the impact of climate change (Fezzi et al. 2014; Mendelsohn, Nordhaus, and Shaw 1994). The Ricardian/Hedonic approach, on its turn, consists in the estimation of a reduced form equation of farmland values/land rents that includes a set of climate variables as regressors. While this approach accounts for adaptation, it does not provide information about farmers' adaptive strategies (Fezzi et al. 2014). Finally, CGE models endogenize prices and account for inter-sectorial and international linkages (Fezzi et al. 2014; Schlenker, Hanemann, and Fisher 2006). However, these advantages come at the cost of aggregated analysis of entire economic sectors. This implies a loss of information regarding heterogeneity and spatial variation in environmental variables (Fezzi et al. 2014).

Recently, some studies have developed structural models to overcome the above listed drawbacks (e.g. Fezzi et al. 2014; Kaminski, Kan, and Fleischer 2012; Ortiz-Bobea and Just 2013). These studies rely on profit maximization to model land allocation and evaluated climate change impacts on agriculture by the equi-marginal principle. This feature explicitly takes into account farmers' adaptation by specifying structural estimable land use equations. Thus, the structural approach reveals the land reallocation mechanisms behind the Ricardian approach. However, structural models fail to measure impacts of climate change on welfare and agriculture yields. This drawback is due to data availability issues related to farm's profits and outputs, inhibiting estimation of all structural parameters (Fezzi and Bateman 2011).

Although the impact of changes in mean temperature and rainfall on agriculture has generated a great deal of interest, the role of variance changes of these climatic variables has not gained similar attention. A larger climatic variance increases the variance of farm profits, which might induce risk-averse farmers to change their decisions. Notwithstanding, few studies have analyzed adaptation strategies to changes in climate variability. A Ricardian study found that climate variability have affected land prices in mid-western U.S. (Kelly, Kolstad, and Mitchell 2005), whilst other found a negative relationship between land prices and rainfall variability in Brazil (Cunha, Coelho, and Féres 2015). Kaminski, Kan, and Fleischer (2012) used a structural model to evaluate the impact of rainfall variability on Israeli agriculture. They found that higher inter-annual rainfall standard deviation is associated to more surface allocated to irrigated crops. However, Kaminski, Kan, and Fleischer (2012) set up a risk-neutral theoretical model. This could prevent correct estimation of parameters, once the certainty results regarding agents behavior are biased if agents are risk-averse (Pope 1982). Coyle (1999) proposed a more suitable approach to incorporate climate variability by considering a risk-averse utility maximization framework. This approach avoids biased estimates by imposing theoretical restrictions on the specifications of the land use model.

In this chapter, we evaluate the impact of climate change and climate variability on land use allocation across forest, cropland and pastures. We estimate a structural land use model featuring risk-averse farmers. Accounting for risk-aversion could partially explain the fact that a low yield activity as grass fed cattle production is the dominant agricultural land use in BLA. Early studies argued that cattle production in BLA is less profitable compared to alternative agricultural activities and attributed this pattern to land speculation (e.g. Fearnside 2005; Hecht 1985, 1993). Recently, some authors stated that this pattern occurs because cattle production in BLA is more profitable than in other Brazilian regions due to a higher productivity and a lower land cost (E. Arima, Barreto, and Brito 2005; Walker et al. 2009). Nevertheless, the latter did not dismiss the profitability gap between cattle production and other agricultural activities. We propose an alternative explanation based on portfolio theory. Pasture for cattle production could be a hedging strategy for risk-averse farmers if other land uses present a higher yield variability related to climate variability. Therefore, farmers would be willing to engage in a less profitable activity, like cattle, if it is also less risky. This behavior presents important policy implications[9]. For instance, there will be more land allocated into pasture in the near future if climate change leads to a higher climate variability.

To properly account for climate variability, we bring together two important strands of the literature in our theoretical model. First, following Chambers and Just (1989), we consider land as a fixed but allocable factor to deal with two aspects of agricultural production: spatially separated production and cross-output interdependence. This is the most frequent approach adopted by risk-neutral land use studies (e.g. Arnade and Kelch 2007; Fezzi and Bateman 2011; Fezzi et al. 2014; Kaminski, Kan, and Fleischer 2012; Lacroix and Thomas 2011). Second, we add risk-aversion related to exogenous climate variables to Chambers and Just (1989) approach. This is a novelty in land use modeling, since risk-averse land use models do not rely on Chambers and Just (1989) approach and do not model climate variability as a source of yield risk (e.g. J.-P. Chavas and Holt 1990; J. Chavas and Holt 1996; Komarek and Macaulay 2013; Lansink 1999).

[9] See Knoke et al. (2011).

The remainder of this chapter is organized in the following way. After this introduction, section 2.2 presents the land use risk-averse model. Section 2.3 discusses the estimation procedure and describes the database. Section 2.4 presents results and the simulation exercises regarding the impact of climate change on land use patterns. Finally, section 2.5 consolidates the main conclusions and points out potential policy implications.

2.2.Land Use Model

Our theoretical model consists of a two-step maximization problem where technology is nonjoint among land uses. However, crops compete for a fixed amount of land, implying land use interdependence[10]. At first-step, farmers maximize utility from each land use given the allocation of land and other fixed inputs. In this step, we show the utility maximization problem under uncertainty in a Coyle's (1999) approach. In the second-step, we treat land and other fixed inputs as fixed but allocable factors, a framework proposed by Chambers and Just (1989).

2.2.1. Uncertainty

Climate uncertainty modeling relies on the assumption that farmers know the probability distribution of climate variables. This is a proxy for farmers' climate perception rather than real farmers' rationalization. They do not know these variables exactly, but they should know which locations have a high level of expected precipitation or high climate variability. We assume that farmers are characterized by a constant absolute risk aversion (CARA) behavior; technology may be described

[10] Chambers and Just (1989) argues that multioutput agricultural production can be described by separate production function wherein the technology is nonjoint in inputs.

according to Just and Pope (1978, 1979) and there is no price uncertainty in our framework. Our approach, rather restrictive, is recurrent in production analysis as it simplifies duality results and empirical applications (Coyle 1999)[11].

The utility function (U) of risk-averse farmer can be represented by his certainty equivalent, which is linear in expected profits ($\bar{\pi}$) and profit variance (σ_π^2)

$$U = \bar{\pi} - (r/2)\sigma_\pi^2 \tag{1}$$

where r is the coefficient of risk-aversion.

Profits from a land use "i" are

$$\pi_i = p_i y_i - wx \tag{2}$$

where p_i is output price related to a land use; y_i is the output quantity related to land use "i"; w is the price vector of variables inputs; and x is the vector of variable inputs.

According to Coyle (1999), the Just and Pope (1978, 1979) production function could take the following form for each land use

$$y_i = a_i(x_i, z_i, l_i) + b_i(x_i, z_i, l_i)^{1/2} d_i(c_1, c_2) \tag{3}$$

[11] These assumptions are not necessarily realistic for BLA. We did not rely on stronger assumptions like Decreasing Absolute Risk Aversion (DARA) utility function due lack of data on farmers' wealth. The lack of data on price variability also prevented us from incorporate price risk.

where z_i is a fixed input, like capital, allocated to production of y_i; l_i is the land allocated to production of y_i; and $d_i(c_1,c_2)$ is a underlying climate attribute variable which is a function of temperature (c_1) and rainfall (c_2).

The first term in the right-hand side of (3) is nonstochastic, since farmer chooses the quantity of variable and fixed inputs to be used in the production of y_i, as well as the surface allocated to this land use. The second term in the right-hand side of (3) is stochastic. Climate attribute is a nonlinear function of stochastic climate variables[12] and $b_i(x_i,z_i,l_i)^{1/2}$ is a term added to account for inputs that increase production variability and inputs that decrease production variability[13].

Using equations (2) and (3), one can show that expected profits ($\bar{\pi}_i$) and profits variance ($\sigma^2_{\pi i}$) are

$$\bar{\pi}_i = p_i a_i(x_i,z_i,l_i) + p_i b_i(x_i,z_i,l_i)^{1/2} d_i(\bar{c}_1,\bar{c}_2) - wx \tag{4}$$

$$\sigma^2_{\pi i} = p_i^2 \sigma^2_{yi} = p_i^2 b_i(x_i,z_i,l_i)\sigma^2_{di}(\sigma^2_{c_1},\sigma^2_{c_2},\sigma_{c_1c_2}) \tag{5}$$

Replacing (4) and (5) in (1) and solving for x_i yields

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[12] This assumption differs from Coyle (1999), where y_i is an increasing function of climate variables. We assume that y_i is an increasing function of $d_i(c_1,c_2)$, a nonlinear function of climate variables.

[13] Just and Pope (1979) pointed out that agriculture output variance is an increasing function of inputs in traditional specifications of production functions. This is not a reasonable result for inputs like pesticides and irrigation equipment, since output variability appears to be a decreasing function in these inputs.

$$v_i(p_i, w, z_i, l_i, \bar{c}_1, \bar{c}_2, \sigma^2_{c_1}, \sigma^2_{c_2}, \sigma_{c_1c_2}) = \max_{x\geq 0}\{p_i\bar{y}_i - wx_i - (r/2)p_i{}^2\sigma^2_{yi}\}$$
$$\equiv \max_{x\geq 0}\{p_i a_i(x_i, z_i, l_i) + p_i b_i(x_i, z_i, l_i)^{1/2} d_i(\bar{c}_1, \bar{c}_2) - wx_i - (r/2)p_i^2 b_i(x_i, z_i, l_i)\sigma^2_{di}(\sigma^2_{c_1}, \sigma^2_{c_2}, \sigma_{c_1c_2})\} \qquad (6)$$

Assuming that indirect utility function $v_i(\cdot)$ exists and is twice differentiable, Coyle (1999, pp.554–555) generalized the duality results under output uncertainty: $v_i(\cdot)$ is linear homogenous in $(p_i, w, 1/\sigma^2_{c_1}, 1/\sigma^2_{c_2}, 1/\sigma_{c_1c_2})$[14]; expected output supply, variable inputs demands and output variance can be recovered by generalizations of Hotelling's lemma ($\bar{y}_i = \partial v_i(\cdot)/\partial p_i + rp_i\sigma^2_{yi}$, $x = -\partial v_i(\cdot)/\partial w$, $\sigma^2_{yi} = -\partial v_i(\cdot)/\partial\sigma^2_{di}(2\sigma^2_{di})/(rp_i^2)$); and $v_i(\cdot)$ is convex in input prices w but not in (p_i, w).

2.2.2. Land as a Fixed but Allocable Factor

We assume that farmers could produce three aggregate outputs related to each land use "i": 1=cropland, 2= pasture and 3=forest. Thus, there is an indirect utility function $v_i(\cdot)$ to each land use. Each farmer has an endowment of land L and other quasi-fixed input Z, which are allocable to different land uses. Following Chambers and Just (1989), the farmer maximizes the constrained problem in l_i and z_i

[14] Linear homogeneity results rely on assumption that $\sigma^2_{di}(k\sigma^2_{c_1}, k\sigma^2_{c_2}, k\sigma_{c_1c_2}) = k\sigma^2_{di}(\sigma^2_{c_1}, \sigma^2_{c_2}, \sigma_{c_1c_2})$. Assuming an optimal x_i in right-hand side of expression (6) and the later assumption yields $v_i(kp_i, kw, z_i, l_i, \bar{c}_1, \bar{c}_2, \sigma^2_{c_1}/k, \sigma^2_{c_2}/k, \sigma_{c_1c_2}/k) = kv_i(p_i, w, z_i, l_i, \bar{c}_1, \bar{c}_2, \sigma^2_{c_1}, \sigma^2_{c_2}, \sigma_{c_1c_2})$.

$$\mathfrak{L} = \sum_{i=1}^{3} v_i(p_i, w, z_i, l_i, \bar{c}_1, \bar{c}_2, \sigma_{c_1}^2, \sigma_{c_2}^2, \sigma_{c_1c_2}) + \lambda\left(L - \sum_{i=1}^{3} l_i\right) + \mu\left(Z - \sum_{i=1}^{3} z_i\right) \quad (7)$$

λ and μ are the Lagrange multipliers for land and other quasi-fixed inputs, respectively. First order conditions for an interior solution of the Lagrangean are expressed by

$$\partial\mathfrak{L}/\partial l_i = \partial v_i(\cdot)/\partial l_i - \lambda = 0 \quad (8)$$

$$\partial\mathfrak{L}/\partial z_i = \partial v_i(\cdot)/\partial z_i - \mu = 0 \quad (9)$$

$$L - \sum_{i=1}^{3} l_i = 0 \quad (10)$$

$$Z - \sum_{i=1}^{3} z_i = 0 \quad (11)$$

According to equation (8), the optimal land allocation occurs when marginal utility equals for all land uses. As expressed in (9), farmers allocate other fixed input to different uses to equal their marginal revenues as well. Constraints in (10) and (11) are binding assuming an interior solution. However, farmers could allocate zero amounts of fixed inputs to a crop, leading to a corner solution (Chambers and Just 1989). When it occurs, the equi-marginal behaviors in (8) and (9) hold for other land uses receiving nonzero allocation. Therefore, equality is replaced by an inequality in (8) and (9) at land use with zero amounts of l_i or z_i.

The system (8)-(11) of 6 equations and 6 unknowns yields optimal solution to the constrained multi-output optimization problem in (7)[15]: $l_i^*(p,w,Z,L,\bar{c}_1,\bar{c}_2,\sigma_{c_1}^2,\sigma_{c_2}^2,\sigma_{c_1c_2})$ and $z_i^*(p,w,Z,L,\bar{c}_1,\bar{c}_2,\sigma_{c_1}^2,\sigma_{c_2}^2,\sigma_{c_1c_2})$. Substituting $l_i^*(\cdot)$ and $z_i^*(\cdot)$ in (10) and (11) yields identities of physical conservation laws (Moore and Negri 1992). Differentiating land identity $L-\sum_{i=1}^{3} l_i^* = 0$ in p, w, Z, L, $\bar{c}_1$, $\bar{c}_2$, $\sigma_{c_1}^2$, $\sigma_{c_2}^2$, and $\sigma_{c_1c_2}$ yields

$$\sum_{i=1}^{3}\frac{\partial l_i^*}{\partial L}\equiv 1;\ \sum_{i=1}^{3}\frac{\partial l_i^*}{\partial Z}\equiv 0;\ \sum_{i=1}^{3}\frac{\partial l_i^*}{\partial p_j}\equiv 0;\ \sum_{i=1}^{3}\frac{\partial l_i^*}{\partial w}\equiv 0$$
$$\sum_{i=1}^{3}\frac{\partial l_i^*}{\partial \bar{c}_h}\equiv 0;\ \sum_{i=1}^{3}\frac{\partial l_i^*}{\partial \sigma_{c_h}^2}\equiv 0;\ \sum_{i=1}^{3}\frac{\partial l_i^*}{\partial \sigma_{c_1c_2}}\equiv 0 \qquad (12)$$

where j = 1 (cropland), 2 (pasture) and 3 (forest); h = 1 (temperature) and 2 (rainfall).

The first identity in (12) states that an additional unit of land should be fully allocated among uses. Other identities state that changes in other variables are fully absorbed within the land endowment L.

Coyle (1999) used normal quadratic (NQ) flexible form to parameterize $v_i(\cdot)$ for empirical purposes[16]. Defining w as agricultural wages and Z a fixed input, $v_i(\cdot)$

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[15] Note that l_i^* and z_i^* is a function of all output prices (p vector) rather than own output price (p_i). This occurs because changes in own price modify marginal utility of a land-use, which lead to changes in other land-use allocation to equate their marginal utilities.

[16] NQ was first proposed by Lau (1976) and is a Taylor's expansion of second order. NQ has the following desirable properties: is self-dual – utility and technology functions are quadratic; the Hessian

linear homogeneity propriety ensures that prices, climate variability and utility could be expressed relative to the price of numéraire input w: $p_i^* = p_i / w$, $\sigma_{c_1}^{2*} = w\sigma_{c_1}^2$, $\sigma_{c_2}^{2*} = w\sigma_{c_2}^2$, $\sigma_{c_1c_2}^{*} = w\sigma_{\epsilon_1\epsilon_2}$, and $v_i^*(\cdot) = v_i(\cdot)/w$. Assuming $n \equiv (n^1, .. n^M) = (p_i^*, z_i, l_i, \bar{c}_1, \bar{c}_2, \sigma_{c_1}^{2*}, \sigma_{c_2}^{2*}, \sigma_{c_1c_2}^{*})$, NQ is expressed as $v_i^*(\cdot) = \alpha_0 + \sum_i \alpha_i n^i + (1/2)\sum_i \sum_j \alpha_{ij} n^i n^j$, with $\alpha_{ij} = \alpha_{ji}$.

When utility functions are NQ, one can write $l_i^*(\cdot)$ as

$$l_i^* = \beta_{0i} + \sum_{j=1}^{3} \beta_{ji} p_j^* + \beta_{4i} L + \beta_{5i} Z + \beta_{6i} \bar{c}_1 + \beta_{7i} \bar{c}_2 + \beta_{8i} \sigma_{c_1}^{2*} + \beta_{9i} \sigma_{c_2}^{2*} + \beta_{10i} \sigma_{c_1c_2}^{*} \quad (13)$$

Restrictions in (12) imply that $\sum \beta_{4i} = 1$ and $\sum \beta_{ji} = 0$ for $j \neq 4$. The effect on land use allocation of a change in variances follows the portfolio theory. For instance, an increase in rainfall variability ($\sigma_{c_2}^2$) will increase yield risk in all three activities *ceteris paribus*. These effects are likely to vary across activities due differences in each climate attribute function $d_i(c_1, c_2)$. The farmer would reallocate land among uses to equate his/her marginal land use utilities and achieve a new equilibrium. The activity which yield risk is less sensitive to the change of climate variability will absorb land

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is a matrix of constants – once reached, optimal sufficient conditions hold globally; the first derivatives are linear in prices and fixed inputs; and maintains linear price homogeneity (Shumway 1983, 749–50). Furthermore, NQ is preferable than traditional Cobb-Douglas and Translog specification because it does not rule out corner solution.

from other uses, as expressed by $\sum \beta_{9i} = 0$. Therefore, the farmer would choose the less risky portfolio given the expected returns.

As Gorddard (2013, p.1114) pointed out, dual results of cross-price symmetry in output supply and input demand do not hold in (13) (i.e. assumption of $\beta_{ji} = \beta_{ij}$ for prices does not occur due to land allocation is a primal result). However, Gorddard (2013) demonstrated an equivalent symmetry result for land as fixed but allocable factor: $\partial l_i / \partial p_j \left({\partial y_i / \partial L} \middle/ {\partial l_i / \partial L} \right) = \partial l_j / \partial p_i \left({\partial y_j / \partial L} \middle/ {\partial l_j / \partial L} \right)$, for $i \neq j$. In other words, cross-price symmetry holds when corrected by marginal effect of L on yields.

2.3. Estimation and Data

A suitable empirical strategy to estimate the system of equation (13) is seemingly unrelated regressions (SUR), once this technique accounts for cross-equational error correlation. However, it does not deal with censoring that arises from corner solutions in the farmer maximization problem. In fact, zero allocation is frequent in farm level analysis and is present in this study, censoring each land use from below. A primary choice to deal with this issue is a SUR-Tobit estimator. However, Shonkwiler and Yen (1999) pointed out that system estimation with censored dependent variables is computationally demanding, since it requires the evaluation of multiple integrals in the likelihood function.

To circumvent this empirical drawback, Shonkwiler and Yen (1999) proposed a consistent two-step estimation for a system of equations with limited dependent variables, avoiding the highly computational burden of the alternative models (Moro and Sckokai 2013). This procedure was first applied to demand analysis, however it presents a widespread use in agricultural production analysis (Goodwin, Vandeveer, and Deal 2004; Goodwin and Mishra 2005; Goodwin and Mishra 2006; Sckokai and Antón 2005; Sckokai and Moro 2006; Sckokai and Moro 2009; Platoni, Sckokai, and Moro 2012).

In our application, the first-step consists in estimating a probit model of land use decisions to retrieve the cumulative distribution function and the normal probability density function for each land use decision. This is a selection step to model binary farmer's decision regarding to set or not to set a land use. Notwithstanding, the main Shonkwiler and Yen (1999) contribution consists in the second-step. They found that the intuitive system of equation generalization of Heckman's sample selection procedure proposed by Heien and Wessells (1990) is not consistent, generating biased unconditional expectations of dependent variables. Furthermore, Shonkwiler and Yen (1999) stated that estimation of a censored system requires a procedure that uses the entire sample since each dependent variable could present a different pattern of censoring in terms of limit and nonlimit outcomes[17]. In order to overcome these latter drawbacks in the second-step procedure, Shonkwiler and Yen (1999) proposed the SUR estimation of the following system for the entire sample in the second-step

$$l_{ij} = \Phi\left(z'_{ij}\alpha_i\right) f\left(x_{ij}, \beta_i\right) + \delta_i \phi\left(z'_{ij}\alpha_i\right) + \xi_{ij}, \quad i = 1,2,3 \qquad (14)$$

[17] For example, a farm with zero land allocation in crop is likely to present nonzero land allocations in other land uses. If this farm is dropped from the second-step estimation due zero allocation in crops, we lose information on nonzero allocation in other land uses.

where j is farms; $f\left(x_{ij},\beta_i\right)$ is the land use allocations equation expressed in (13); $\Phi\left(z'_{ij}\alpha_i\right)$ and $\phi\left(z'_{ij}\alpha_i\right)$ are the cumulative distribution function and normal density function, respectively, obtained in the first-step; δ_i is the unknown coefficient of correction factors; x_{ij} and z_{ij} are vectors of exogenous variables[18]; α_i and β_i are vectors of first and second-step parameters, respectively; and ξ_{ij} is the error term with zero mean.

The Shonkwiler and Yen (1999) procedure has received criticism due its lack of estimation efficiency related to its heteroskedastic errors (Tauchmann 2005, 2010). To deal with this drawback and improve estimation efficiency, we estimated (14) and bootstrapped the residuals with 300 replications clustered by municipality, which also dealt with potential spatial autocorrelation. We estimated the first-step in a probit multivariate system by a methodology proposed by Roodman (2011), which provides enhanced estimates by considering potential correlation of errors term in probit equations (Platoni, Sckokai, and Moro 2012). Adding-up restrictions for observed land allocations leads to a singular estimation matrix. In order to overcome the singularity problem, system (14) was estimated by excluding the forest equation. Once crop and pasture equation parameters are estimated, forest coefficients can be recovered from the restrictions expressed by (12).

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[18] As in traditional sample selection models, x_{ij} is a subset of z_{ij} and the later are the explanatory variables in the first-step. Platoni et al. (2012) suggests the addition of demographic variables in x_{ij} to build z_{ij}.

2.3.1. Data

We used data from Brazilian Agricultural Census of 2006 on land use pattern, a proxy to capital endowment and agricultural wages. The Brazilian Institute of Geographic and Statistics (*Instituto Brasileiro de Geografia e Estatística* – IBGE) provides this information on municipal level segmented into five land tenure groups (owner, sharecropper, renter, occupant and farmers recently granted in land reform (less than five years)) and eleven farm-size groups[19]. We created representative farms from averages of each group formed from a municipality "i", land tenure "j" and farm size group "k". Thus, each municipality could present up to 55 of these representative farms. Pasture allocations are the sum of native and cultivated pastures, while forestland is obtained by adding up native and cultivated forests. Cropland is computed in a residual manner, by subtracting pasture and forest from total area[20]. We did not use the cropland allocations present in the census to avoid double counting, as the same surface would be used to grow more than one crop within a year. For example, in some BLA regions farmers grow soybean during spring/summer and maize during autumn/winter in the same surface. Total farm area and all land allocations are expressed in hectares (10,000m^2). A proxy for capital is the declared value of all vehicles in each representative farm in *real* (Brazilian currency), and represents tractors and other vehicles used in agricultural production. Wages are computed as the value of total wages paid to workers divided by a labor variable equivalent to an eight hours workday.

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[19] This is a special tabulation of Census constructed from IBGE microdata. We are grateful to Eustáquio Reis from IPEA for providing us this dataset.

[20] In computing total farm area, we ignored buildings areas, areas covered with water and land unsuitable to agriculture.

Prices of cropland and forest products are regional price indexes for the 1996-2005 calculated from data of IBGE yearly agricultural and forestry surveys (*Produção Agrícola Municipal* and *Produção da Extração Vegeral e da Silvicutura*, respectively). Crop prices index aggregates prices of 18 agriculture products that corresponds to 98.4 % of agricultural production value in Amazon in 2006[21]. Forest prices aggregate six products of natural and planted forest, covering 98.1% of forest production[22]. We deflated the value of production to 2005 values using the General Index Price provided by Institute for Applied Economic Research (*Instituto de Pesquisa Econômica Aplicada* – IPEA) website (www.ipeadata.gov.br). The real prices for each product are the quotient between the value of production for 1996-2005 period and the amount of production for the same period. We calculated the index for each municipality using the formula: $RPI = \sum_{j=1}^{n} q_{ij} p_{ij} \Big/ \sum q_{ij} \overline{p}_j$. Where i are the municipalities; j are the 18 agricultural products or the 6 forest products, q_{ij} is the amount produced of j in municipality i; p_{ij} is the average real price of product j in municipality i; $\overline{p}_j$ is the average price of product j in Legal Amazon. Pasture output prices are the municipal cattle price for 2001 computed by Arima et al. (2007). This is an average farm-gate price by municipality built from slaughterhouses beef prices discounting the transportation costs. We normalized prices indexes and wages index at the mean and multiplied by 100.

Climate variables were provided by Professor Claudio Araujo from Centre d'Études et de Recherches sur le Développment International (CERDI)/Université

[21] Pinapple, cotton, rice, sugar cane, beans, cassava, watermelons, maize, soybean, banana, ruber, cocoa, coffee, coconut, palm oil, oranges, and black pepper.

[22] Açaí, babaçu, charcoal, Brazilian nut, firewood, and timber.

d'Auvergne, France. This database consists in the Willmott, Matsuura and Collaborator's (http://climate.geog.udel.edu/~climate/) data on monthly temperature (in Celsius degree) and rainfall (in millimeters) converted to Brazilian municipalities boundaries by Simonet (2013). We built the climate variables as follows. Mean temperature is the average annual mean temperature. Accumulated rainfall is the average of annual accumulated rainfall. Inter-annual temperature variance is the variance of annual average temperature. Inter-annual rainfall variance is the variance of annual accumulated rainfall. Inter-annual climate covariance is covariance of annual mean temperature and annual accumulated rainfall. Intra-annual temperature variance is the average between years of monthly temperature variance within years. Intra-annual rainfall variance is the average between years of monthly rainfall variance within years. Intra-annual climate covariance is the average between years of monthly temperature and rainfall covariance within years. The first five variables are the climates variables in expression (13). Inter-annual variances and covariance provide information about probability of a year with extremes climate events, such a drought or a higher temperature. Intra-annual variances and covariance provide information on the average seasonal pattern. Municipalities with higher average intra-annual variances indicate that seasons are more heterogeneous. Positive intra-annual covariance indicates that temperature and rainfall move in the same direction in the seasons. Negative intra-annual covariance indicates that these variables move in different directions. We built climate variables for three time spans (1946-2005, 1966-2005, and 1986-2005) to explore farmer's different behavior with respect to time horizon of climate variables.

Table 1 presents the descriptive statistics of the variables used in the land use model. The dataset covers 1,623,901 farms aggregated into 7089 representative farms.

The mean price indexes and wages index differ from 100 because we dropped some missing values in other variables. Regarding censoring in land use, 2% of the sample presented zero allocation in cropland, 14% in pasture, 17% in forest. The only climate variables that substantially differ between the three periods are inter-annual rainfall variance, inter-annual climate covariance and intra-annual climate covariance. Inter-annual rainfall variance has decreased in last period compared to the two previous, as well its variability between municipalities. Absolute inter and intra-annual climate covariance increased over the period. Linear homogeneity is imposed by dividing all price indexes by wages. Similarly, we multiply inter-annual variances and inter-annual climate covariance by wages. Intra-annual variables appear in the models without transformations.

Some studies have used degree days instead of temperature to measure climate change impact on agriculture in temperate zones (e.g. Deschênes and Greenstone 2007; Kaminski, Kan, and Fleischer 2012; Schlenker, Hanemann, and Fisher 2006). They modeled the impact of temperature by the number of the days which temperature lied within some interval. The most frequent interval is 8°C-32°C. Temperatures lying within this interval account for a favorable day and lying outside account for a harmful day. As one can see in Table 1, temperature in Amazon is far above from 8°C. Even extremes of mean temperatures and temperature variance variables indicate that this temperature is unlikely. The upper bound is more likely to be reached in Amazon. Although the degree days approach is relevant, we use temperature due to data availability issue. However, we expected this would not undermine our estimates because the above-mentioned degree days interval was set to agriculture in temperate latitudes. Thus, the upper bound could be greater to agriculture in equatorial/tropical latitudes within Brazilian Legal Amazon.

Table 1. Descriptive statistics of variables of interest in BLA[a]

	mean	sd	cv	min	max
Cropland (ha)	15.90	137.72	8.66	0.00	6908.71
Pasture (ha)	107.69	626.66	5.82	0.00	16017.40
Forest (ha)	89.93	679.16	7.55	0.00	22569.51
Land (ha)	213.52	1257.12	5.89	0.00	33329.84
Capital (R$)	23349.90	386278.88	16.54	0.00	24230400.00
Observations per representative farms	229.07	420.65	1.84	3.00	6095.00
Crop price index	99.85	34.55	0.35	47.17	350.05
Cattle price index	99.95	15.57	0.16	7.64	120.58
Forest price index	99.48	38.27	0.38	29.39	347.61
Wages index	102.73	123.33	1.20	5.70	769.43
Mean temperature (Celsius)					
1946-2005	25.36	1.20	0.05	17.85	28.20
1966-2005	25.47	1.19	0.05	17.95	28.40
1986-2005	25.76	1.17	0.05	18.40	28.61
Accumulated rainfall (mm)					
1946-2005	1883.99	394.72	0.21	1102.71	3052.11
1966-2005	1903.72	397.63	0.21	1138.36	3066.16
1986-2005	1896.75	423.37	0.22	1078.70	3163.58
Inter-annual temperature variance (Celsius^2)					
1946-2005	35.77	73.06	2.04	0.62	851.99
1966-2005	40.90	86.92	2.13	0.64	1022.47
1986-2005	32.24	71.01	2.20	0.65	802.26
Inter-annual rainfall variance (mm^2)					
1946-2005	5787212.92	7498822.49	1.30	4108.24	1.99e+08
1966-2005	5614384.84	6953624.49	1.24	3794.73	1.87e+08
1986-2005	4554352.62	5365889.86	1.18	2641.23	76947880.00
Inter-annual climate covariance					
1946-2005	656.44	2955.18	4.50	-10896.02	20827.44
1966-2005	187.21	2492.54	13.31	-17618.38	14694.88
1986-2005	2031.04	3314.36	1.63	-12659.48	25248.94
Intra-annual temperature variance (Celsius^2)					
1946-2005	0.96	0.91	0.95	0.23	4.78
1966-2005	0.95	0.89	0.94	0.22	4.66
1986-2005	0.99	0.87	0.88	0.25	4.81
Intra-annual rainfall variance (mm^2)					
1946-2005	16781.00	5164.83	0.31	6823.20	42555.24
1966-2005	16537.93	5017.32	0.30	6410.68	43196.08
1986-2005	16327.86	5130.14	0.31	7052.56	42435.86
Intra-annual climate covariance					
1946-2005	-3.50	57.88	-16.56	-126.41	225.80
1966-2005	-3.18	57.60	-18.13	-124.93	226.66
1986-2005	-12.68	59.16	-4.66	-125.70	207.22

a. Cropland, pasture, forest, land, and capital vary between and within municipalities. Other variables vary only between municipalities. sd – standard deviations; cv – coefficient of variation; min – minimum; max – maximum.

We have observations for only a year, preventing us from properly controlling for unobserved heterogeneity among municipalities. To partially deal with this issue, we add some variables that could be heterogeneity sources. The first set of variables is land tenure dummies obtained from representative farms groups, where the reference is owners. The second set of variables represents agronomic features such soil, topography, biome, and latitude. The first two variables are the percentage of the municipality area covered by eight soil and five topography classes. These classes range to less suitable to more suitable to agriculture. The reference for soil is soil class

1 and the reference for topography is topography class 2. We did not use topography 1 in estimations because it is rare class within Amazon, which could lead to multicolinearity. To account for biome differences, we introduced the percentage of municipalities areas covered with cerrado biome. We expect that the forest output bundle in cerrado differ from Amazon, the dominant biome within BLA. For example, vegetation in cerrado is sparser than in Amazon biome. Thus, it is less productive in wood products. This could affect the forest profits as well as land use allocation. Soil, topography, and biome data are provided by the Center for Studies and Spatial Systemic Models (*Núcleo de Estudos e Modelos Espaciais Sistêmicos* - NEMESIS). Latitude controls, among other factors, for the incidence of solar radiation. This variable is the absolute latitude of municipalities centroids provided by IBGE. The third set of variables relates to institutional environment indicators provided by Catholic Pastoral Land Commission for 2005. These variables are the number of rural conflicts per municipality, the number of murders and murders attempts related to land per municipality, and the number of farms caught with slavery and poor work conditions per municipality. Araujo et al. (2009) showed that these institutional variables are associated to property rights in BLA and weak property rights increases deforestation.

Demographic variables for probit first-step estimation are the proportion of farms within a representative farm with the following features: managed by women, the manager is younger than 25, the manager is older than 55, the manager has more than ten years of experience in agriculture, the manager studied less than eight years. All demographic variables are from Brazilian Agricultural Census of 2006. Table 2 presents descriptive statistics of the latter variables and of the controls variables.

Table 2. Descriptive statistics for control variables and first-step variables

	mean	sd	cv	min	max
Owner (proportion)	0.6775	0.4675	0.69	0.00	1.0
Settled (proportion)	0.1114	0.3147	2.82	0.00	1.0
Renter (proportion)	0.0525	0.2230	4.25	0.00	1.0
Sharecropper (proportion)	0.0523	0.2227	4.26	0.00	1.0
Ocupant (proportion)	0.1062	0.3081	2.90	0.00	1.0
% soil type 1	4.2727	16.2268	3.80	0.00	100.0
% soil type 2	3.6750	16.2344	4.42	0.00	100.0
% soil type 3	3.0463	12.7680	4.19	0.00	100.0
% soil type 4	44.7235	38.6824	0.86	0.00	100.0
% soil type 5	2.5322	12.9147	5.10	0.00	99.4
% soil type 6	4.6935	16.9302	3.61	0.00	100.0
% soil type 7	0.3677	3.8447	10.46	0.00	72.0
% soil type 8	36.6785	38.8318	1.06	0.00	100.0
% topography type 2	36.6785	38.8318	1.06	0.00	100.0
% topography type 3	4.2275	16.5783	3.92	0.00	100.0
% topography type 4	56.1215	38.6304	0.69	0.00	100.0
% topography type 5	2.4959	12.9113	5.17	0.00	99.4
Latitude (dgrees)	7.2154	4.3461	0.60	0.03	16.8
%Cerrado	31.5411	44.3547	1.41	0.00	100.0
Conflict (occurrence)	0.6609	1.5248	2.31	0.00	15.0
Slavery/Poor work conditions (occurrence)	0.4967	1.8583	3.74	0.00	20.0
Murder/Attempts (occurrence)	0.0664	0.4206	6.33	0.00	5.0
Education (proportion)	0.3083	0.1184	0.38	0.00	1.0
Experience (proportion)	0.1869	0.1092	0.58	0.00	1.0
Women (proportion)	0.0344	0.0413	1.20	0.00	0.7
Younger than 25 (proportion)	0.0166	0.0298	1.80	0.00	0.6
Older than 55 (proportion)	0.1259	0.0810	0.64	0.00	1.0

sd – standard deviations; cv – coefficient of variation; min – minimum; max – maximum.

2.4.Results

Results for the climate variables for three different time spans (1946-2005, 1966-2005, and 1986-2005) are in Table A2, Table A3 and Table 3 respectively[23]. There are three specifications in each of the three tables. Column 1 presents results using only land tenure as control variables. Column 2 presents results controlling for land tenure and agronomic variables. Column 3 introduces institutional variables as additional controls. We presented results in this way to verify parameters stability related to control variables. We suppressed control variables parameters to save space. Thus, we do not report results for land tenure dummies, soil quality, topography

[23] Table A2 and Table A3 are presented in the appendix, since the results for the 1986-2005 in Table 3 presented a better fit. First-step estimations considering the different climate variables time span are also in appendix: Table A4, Table A5 and Table A6, respectively. In the first-step tables, we do not report control variables results as well as demographic variables results.

quality, latitude, cerrado share, conflicts, slavery/poor work conditions, and murder/attempts.

Results for the 1946-2005 time span do not show a strong relationship between land use allocation and climate variables. The significant climate variables in each specification are accumulated rainfall and intra-annual temperature variance in the pasture equation. Accumulated rainfall coefficients for cropland become significant in the column 2 and 3. Accumulated rainfall and intra-annual coefficients in pasture equation present an absolute increase when we introduce agronomic variables. Inter-annual temperature variance coefficient for cropland equation is significant at 10% in column 1 and become not significant as we introduced controls. Inter-annual rainfall variance coefficient for pasture equation has a similar path.

Results for the climate variables in 1966-2005 time span indicates a stronger relationship between land use and climate compared to 1946-2005. Results for accumulated rainfall and intra-annual temperature variances are similar to 1946-2005 period. Inter-annual temperature variance is significant in all three specifications for cropland. The parameter of inter-annual rainfall variance in pasture equation decays as we introduce controls. Intra-annual temperature variance in cropland equation is now significant at 5% in all columns. Coefficients of inter-annual climate covariance for cropland equation and intra-annual rainfall variance are significant at 10% in column 3.

Climate variables retrieved from 1986-2005 time span presents similar results to the 1966-2005 period (Table 3). Inter-annual climate covariance is no longer significant for cropland in column 3, as well as intra-annual rainfall variance for pasture in column 3. The coefficients of inter-annual rainfall variance in pasture equations are greater than the previous time span. Hence, rainfall variability for 1986-2005 period appears to have a stronger influence on land use decision in BLA.

Table 3. Land use equations parameters estimations for 1986-2005 climate variables for BLA in 2006

	(1)		(2)		(3)	
	Cropland	Pasture	Cropland	Pasture	Cropland	Pasture
Crop price	2.683***	-0.0561	2.804***	0.0664	2.581**	-0.384
	(0.904)	(1.519)	(1.043)	(1.552)	(1.035)	(1.618)
Cattle price	-1.772*	2.461	-1.465	-0.332	-0.900	0.0964
	(1.032)	(1.696)	(1.000)	(2.285)	(1.091)	(2.570)
Forest price	-1.549**	-0.865	-1.312*	-1.102	-1.393**	-1.244
	(0.687)	(0.984)	(0.682)	(1.093)	(0.687)	(1.223)
Land	0.0583***	0.446***	0.0582***	0.446***	0.0573***	0.446***
	(0.0115)	(0.0404)	(0.0115)	(0.0404)	(0.0116)	(0.0402)
Capital	0.0000240	0.0000306	0.0000244	0.0000315	0.0000250	0.0000313
	(0.0000709)	(0.0000874)	(0.0000716)	(0.0000875)	(0.0000726)	(0.0000872)
Mean temperature	0.980	-5.349	1.264	-0.955	1.516	0.763
	(3.039)	(6.252)	(3.131)	(6.040)	(3.144)	(5.830)
Accumulated Rainfall	0.00701	-0.0307***	0.0138**	-0.0500**	0.0119*	-0.0474***
	(0.00448)	(0.0106)	(0.00685)	(0.0196)	(0.00651)	(0.0179)
Inter-annual temperature variance	0.172**	-0.0688	0.139**	0.00226	0.137**	-0.0121
	(0.0689)	(0.0865)	(0.0661)	(0.0822)	(0.0644)	(0.0790)
Inter-annual rainfall variance	-0.000000921	0.00000484***	-0.000000757	0.00000352**	-0.000000727	0.00000324**
	(0.000000828)	(0.00000183)	(0.000000793)	(0.00000150)	(0.000000756)	(0.00000148)
Inter-annual climate covariance	0.00265	-0.00467	0.00246	-0.00402	0.00244	-0.00444
	(0.00227)	(0.00330)	(0.00224)	(0.00306)	(0.00213)	(0.00301)
Intra-annual temperature variance	6.802	23.58**	2.104	28.49**	0.791	28.35**
	(4.305)	(10.50)	(4.126)	(11.48)	(3.973)	(11.44)
Intra-annual rainfall variance	0.000386	0.00111	0.0000379	0.00192	0.0000411	0.00203
	(0.000507)	(0.00120)	(0.000572)	(0.00138)	(0.000574)	(0.00138)
Intra-annual climate covariance	-0.0733	-0.206	-0.0129	-0.115	0.0181	-0.0522
	(0.109)	(0.176)	(0.118)	(0.221)	(0.114)	(0.222)
Constant	-47.04	155.6	-504.9	2994.4	-32.83	4357.5
	(76.21)	(164.8)	(3720.9)	(18342.9)	(4063.5)	(18402.6)
Land tenure	yes		yes		yes	
Agronomic	no		yes		yes	
Institutions	no		no		yes	

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Results in Table A2, Table A3 and Table 3 could present bias due to omitted variables related to specific municipality characteristics, once we could not use panel data techniques. Nonetheless, when we successively added controls variables associated to these specific characteristics, most of climate coefficients remained stable. Although we cannot rule out the possibility that other factors are causing this statistical relationship, the overall pattern within each period appears robust. Climate variables for the 1986-2005 interval have a more consistent relationship with land allocation equations. This is likely to happen for at least two reasons. First, farmers in BLA would take in account climate information from a closer and narrower time horizon. Thus, climate information from 1986-2005 time span presents stronger results in magnitude and statistical significance. Second, remote climate data would be more imprecise than estimates in near past due measurement errors. As a result, estimated coefficients are likely to be biased toward zero. Hence, we chose column 3 in Table 3 as a baseline model. Although there is no consensus in literature regarding time span to retrieve climate variables, our choice agrees with recent structural applications. For instance, Kaminski, Kan, and Fleischer (2012) used an interval of 20 years while Fezzi et al. (2014) used an interval of 30 years.

Robustness checks for the baseline model are in Table 4. The first robustness check relates to irrigated agriculture. Schlenker, Hanemann, and Fisher (2005, 2006) pointed out that water supply is endogenously determined in areas with irrigation. Thus, land use allocation in these areas is not a function of rainfall and coefficients related to rainfall are likely to be underestimated. To check this bias source, we estimated the baseline model without municipalities with a significant irrigated agriculture. We dropped municipalities where irrigated agriculture covered more than 5% of the agricultural land in 2006 or municipalities with more than 15% of census' respondents using irrigation. We lost 249 observations in these municipalities. This classification of irrigated agriculture is equivalent to Cunha, Coelho, and Féres (2015) in a study for Brazil. They considered "municipalities with irrigated agriculture" those with more than 7.4% of total cropland using irrigation. Results for municipalities without irrigation are in column 1 (Table 4). They appear qualitative close to the baseline model. In fact, accumulated rainfall coefficients are overestimated and inter-annual rainfall variance coefficients are underestimated in the baseline model compared to column 1 in Table 4. Thus, irrigated agriculture does not appear to be a great source of bias for land use estimation in BLA.

Table 4. Land use equations parameters estimations for 1986-2005 climate variables without municipalities with irrigation or without representative farms with few respondents for BLA in 2006[24]

	(1)		(2)		(3)	
	Cropland	Pasture	Cropland	Pasture	Cropland	Pasture
Crop price	2.062***	-0.144	1.775***	-0.959	1.086*	-0.886
	(0.639)	(1.804)	(0.645)	(1.119)	(0.642)	(0.855)
Cattle price	-0.849	-0.0487	0.0644	-0.326	-0.0859	2.073
	(0.904)	(2.633)	(0.879)	(1.858)	(0.605)	(1.354)
Forest price	-1.059**	-1.111	-0.860**	-0.484	-0.239	-1.091*
	(0.428)	(1.190)	(0.413)	(0.893)	(0.295)	(0.594)
Land	0.0563***	0.451***	0.0866***	0.362***	0.0369***	0.557***
	(0.0113)	(0.0372)	(0.0302)	(0.0684)	(0.0125)	(0.0504)
Capital	0.0000257	0.0000300	0.0000470	-0.0000132	0.0000562	-0.0000662
	(0.0000707)	(0.000107)	(0.000148)	(0.000123)	(0.0000633)	(0.0000771)
Mean temperature	0.953	0.325	1.699	0.734	0.825	0.604
	(3.144)	(6.178)	(2.699)	(3.963)	(0.906)	(2.792)
Accumulated Rainfall	0.00958*	-0.0458**	0.00440	-0.0319***	0.00464	-0.0231***
	(0.00507)	(0.0187)	(0.00513)	(0.0123)	(0.00372)	(0.00772)
Inter-annual temperature variance	0.141**	-0.0257	0.0606	-0.0547	0.0262	-0.0455
	(0.0606)	(0.0770)	(0.0372)	(0.0478)	(0.0198)	(0.0368)
Inter-annual rainfall variance	-0.000000790	0.00000360**	-0.000000512	0.00000266**	-3.98e-09	0.00000149*
	(0.000000726)	(0.00000168)	(0.000000683)	(0.00000112)	(0.000000268)	(0.000000863)
Inter-annual climate covariance	0.00259	-0.00484	0.00271	-0.00344*	0.000965*	-0.000839
	(0.00189)	(0.00315)	(0.00188)	(0.00186)	(0.000493)	(0.00114)
Intra-annual temperature variance	-0.644	30.23***	-5.631	24.73**	-4.742**	14.32***
	(3.971)	(11.12)	(3.434)	(9.702)	(2.097)	(5.285)
Intra-annual rainfall variance	0.000314	0.00191	0.000209	0.00220**	0.0000332	0.00105*
	(0.000576)	(0.00160)	(0.000628)	(0.000957)	(0.000277)	(0.000583)
Intra-annual climate covariance	0.0317	-0.0985	0.103	-0.118	0.0707**	-0.0785
	(0.114)	(0.245)	(0.0907)	(0.148)	(0.0339)	(0.0869)
Constant	264.7	4031.0	160.1	4577.4	385.6	2157.3
	(4903.8)	(16900.3)	(6534.6)	(22755.8)	(1478.9)	(12693.4)
Observations	6840		6381		5447	

(1) Without municipalities with irrigation, (2) without representative farms with less than 15 respondents, and (3) without representative farms with less than 30 respondents. Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

[24] Table 4 first-step estimations are in Table A7.

Another source of bias is measurement errors in dependent variables. If a respondent declared a wrong land use allocation, this error has a greater weight in representative farm with less respondents. The effect of this measurement error tends to zero as the number of respondents tend to infinite within a representative farm. If there is no correlation between measurement errors and explanatory variables, the standard deviations are inflated. If this correlation exists, the estimated coefficients are biased. To verify these possible biases, we estimated the baseline model without representative farms with less than 15 and 30 respondents. The results are in columns 2 and 3 in Table 4, respectively. We lost 708 observations in column 2 and 1642 observation in column 3. Compared to baseline model, accumulated rainfall coefficients decay in columns 2 and 3 in both land use equations. These coefficients are no longer significant for crop equations. Inter-annual temperature variance in cropland equation becomes not significant in columns 2 and 3. There is a reduction in coefficients of inter-annual rainfall variance in pasture equation in both columns. Some coefficients of inter-annual climate covariance, intra-annual temperature variance, intra-annual rainfall variance and intra-annual climate covariance become significant at 5% or 10%. We could not know the extent of the estimation changes are due to reduction of measurement error or to the restricted dataset, but results are qualitative similar to baseline model for accumulated rainfall and inter-annual rainfall variance.

In Table 5, we reproduce column 3 from Table 3 and add a sub-column with parameters of forest equation. We retrieved the latter parameters from restrictions in expression (12), and tested their significance by Wald test. Thus, forest column presents χ^2 statistic instead of standard deviations. We also expose results considering a risk-neutral model to compare the results under different assumptions regarding risk[25]. Risk-neutral model presents similar coefficients for climate variables. Thus, risk-neutral model will underestimate land conversion from forests to pasture compared to the risk-averse specification if inter-annual climate variability increases in the future. Although we cannot show the degree of risk-aversion of farmers in BLA, the significant coefficients of inter-annual rainfall variance and inter-annual temperature present evidences that farmers are risk-averse.

Overall, the results from all robustness checks are reassuring. Hence, we could consider risk-averse specification in Table 5 as a baseline model and explore its results. Own price coefficients are positive and significant at 5% for cropland and forest. Forest price coefficients are negative and significant at 5% in cropland equation. Other price coefficients are not significant at 10%; however, only cattle price in forest equation presents an unexpected signal. Land coefficients are significant at 1% in all land allocations equations. Pasture and forest absorb a greater amount of an increase in land endowment than cropland. Capital coefficients are not significant at 10% in all equations as well as coefficients of mean annual temperature. An increase in annual accumulated rainfall is negatively associated with land allocation in pasture and positively with forest and crops. A municipality with a higher inter-annual temperature variance presents more land allocated in crops. Farmers facing higher inter-annual rainfall variance allocate more of their land in pasture and less in forest. Intra-annual temperature coefficients are significant at least at 5% in pasture and forest equation. Their signs indicate that farmers facing seasons that are more heterogeneous in

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[25] One can easily derive land use equations for a risk-neutral farmer. In this case, r is zero in expression (6) and climate variances and covariance does not enter in agent's utilities. Therefore, inter-annual climate variances and covariance do not appear in land use equations of a risk-neutral agent. We keep intra-annual variables to control for seasonality pattern.

temperature allocate more land in pasture and less land in forest. Finally, a greater rainfall variation between seasons makes farmers allocate less land in forests.

Table 5. Baseline parameters estimate (risk-averse) for land use and its risk-neutral counterpart for BLA in 2006.

	Risk-averse			Risk-neutral		
	Cropland	Pasture	Forest	Cropland	Pasture	Forest
Crop price	2.581**	-0.384	-2.196	2.404**	-0.668	-1.736
	(1.035)	(1.618)	(1.72)	(1.041)	(1.609)	(1.08)
Cattle price	-0.900	0.0964	0.803	-1.484	-1.265	2.740
	(1.091)	(2.570)	(0.10)	(0.979)	(2.244)	(1.43)
Forest price	-1.393**	-1.244	2.636**	-1.166*	-1.009	2.174**
	(0.687)	(1.223)	(4.52)	(0.680)	(1.161)	(3.30)
Land	0.0573***	0.446***	0.496***	0.0578***	0.447***	0.496***
	(0.0116)	(0.0402)	(146.35)	(0.0117)	(0.0401)	(146.78)
Capital	0.0000250	0.0000313	-0.0000563	0.0000256	0.0000319	0.0000576
	(0.0000726)	(0.0000872)	(0.25)	(0.0000732)	(0.0000873)	(0.25)
Mean temperature	1.516	0.763	-2.279	0.0104	2.060	-2.070
	(3.144)	(5.830)	(0.24)	(3.684)	(6.176)	(0.19)
Accumulated Rainfall	0.0119*	-0.0474***	0.0356**	0.0114*	-0.0454**	0.0340*
	(0.00651)	(0.0179)	(4.36)	(0.00591)	(0.0188)	(3.45)
Inter-annual temperature variance	0.137**	-0.0121	-0.125			
	(0.0644)	(0.0790)	(1.83)			
Inter-annual rainfall variance	-0.000000727	0.00000324**	-0.00000250*			
	(0.000000756)	(0.00000148)	(3.16)			
Inter-annual climate covariance	0.00244	-0.00444	0.00200			
	(0.00213)	(0.00301)	(0.60)			
Intra-annual temperature variance	0.791	28.35**	-29.14***	4.305	29.46***	-33.76***
	(3.973)	(11.44)	(6.82)	(4.524)	(10.99)	(9.23)
Intra-annual rainfall variance	0.0000411	0.00203	-0.00207*	0.0000996	0.00286*	0.00296**
	(0.000574)	(0.00138)	(2.98)	(0.000657)	(0.00147)	(5.72)
Intra-annual climate covariance	0.0181	-0.0522	0.0341	0.00661	0.0360	-0.0426
	(0.114)	(0.222)	(0.03)	(0.130)	(0.230)	(0.05)
Constant	-32.83	4357.5	-4324.6	4.584	4146.9	-4151.4
.	(4063.5)	(18402.6)	(0.08)	(3560.4)	(17674.3)	(0.08)

Standard errors in parentheses for cropland and pasture equations, and χ^2 statistic for forest equations: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

One should carefully interpret the results in Table 5. For example, the signs for accumulated inter-annual rainfall variances indicate that an increase in rainfall variance leads to a decrease in land allocated in forests and to an increase in land allocated in pasture. However, this does mean that an increase in inter-annual rainfall variance decrease yield variability of cattle. This result follows from portfolio theory.

An increase in rainfall variance leads to an increase in yield variability in both activities. Nonetheless, results indicate that the impact is greater for forest. Thus, risk-averse farmers increase pastureland and decrease forestland to equal shadow-prices of each activity, once they prefer a less risky activity. This explanation also applies to inter-annual temperature variance. A higher temperature variance favors land allocation in crops and reduces the amount of land allocated in other uses.

Risk-aversion could partly explain the fact that pasture is the dominant agricultural land use in BLA. Price coefficients are not statistically significant in the baseline estimation for pasture. Thus, these market variables do not appear to be an expressive determinant of land allocation in pasture across BLA. However, pasture allocations positively respond to rainfall variability. In this sense, farmers in BLA allocate land into pasture instead of other uses to reduce their risk exposures. Therefore, cattle production could be classified as a store of value that presents a lower relative risk.

The interpretation of coefficients for accumulated rainfall is more straightforward. Sombroek (2001) pointed out that wetter areas in Amazon are less attractive to cattle production due to a higher incidence of parasites and insect pests. Our results show a similar pattern, as a higher annual accumulated rainfall is associated to less land allocated to pasture. Chomitz and Thomas (2003) found an analogous result, whereas the higher is the precipitation, the smaller is the probability that land is intensively stocked with cattle. However, our results for cropland differ from Sombroek (2001) and Chomitz and Thomas (2003). They argued that a higher precipitation is harmful to annual crops because it inhibits mechanization and because cloud cover limits the amount of sunlight. We found that an increase in rainfall is beneficial to the establishment of crops.

Our results indicate that deforestation is a strategy of adaptation to climate change if it leads to a decrease of annual accumulated rainfall and to an increase in inter-annual rainfall variability in Amazon. To simulate these impacts, we used the downscaled Eta-HadGEM2-ES climate model developed by *Instituto Nacional de Pesquisas Espaciais* (INPE), which is based on the Hadley Center (HadGEM2-ES) global circulation model. Climate projections are related to the Representative Concentration Pathway (RCP) 8.5 proposed by the 5th Assessment Report of Intergovernmental Panel on Climate Change (IPCC 2014). This scenario considers very high GHG emissions in the future and climate projections suggest an increase of 2.6ºC-4.8ºC in global temperature by the end of XXI century related to the 1986-2005 period[26]. The climate model provides projections for the 2010-2040, 2041-2070 and 2071-2099 periods. We calculate the change in average annual rainfall by the difference between the project rainfall in each future period and the Eta-HadGEM projections for 1961-2005 period. We utilized the Eta-HadGEM projections for 1961-2005 period instead of the actual rainfall. Albeit GCMs fail to calculate the actual climate variables, they provide good estimates of climate anomalies. To account for climate variability in our simulation, we will present three scenarios for inter-annual temperature variance and inter-annual rainfall variance: no increase in climate variability, 5% increase in climate variability, 10% increase in climate variability. We used all parameters of accumulated rainfall, inter-annual temperature and rainfall variance of the risk-averse specification in Table 5 to simulate the climate change impact on land use. We did not rule out non-significant coefficients for these variables

[26] Most papers on climate change impacts utilizes more than one GCM and two IPCC emission scenarios. We have utilized the HadGEM2-ES 8.5 because it was the only AR5 projection that we have had access for Brazilian municipalities.

to ensure complete land re-allocation. To evaluate the impact of climate change, we hold other variables at the baseline as well as technology. Thus, these scenarios provide *ceteris paribus* illustrative projections of climate change impact, rather than projections of the future, that can be used to justify changes in those fixed factors as policy responses (Fezzi et al. 2014). We also assume that intra-annual variances and covariance do not change, keeping the baseline seasonal pattern

Table 6 presents simulations for the average representative farm in BLA. The 2025, 2055 and 2085 scenarios represent the changes in 2010-2040, 2041-2070, and 2071-2099 periods, respectively. Related to the 2006 as a baseline, the average BLA representative farm will face a reduction in annual accumulated rainfall of 266.5 mm in 2025, 219 mm in 2055, and 369.8 mm in 2085. Simulations in Table 6 indicate that land allocated to pasture will increase in all scenarios compared to baseline whilst land allocated in cropland and forest will decrease. In general, land use changes in 2025 are greater than in 2055. This is because expected rainfall variation in the second period is smaller than in the first. However, the 2085 land use simulation predicts the greater land use changes. Increases in inter-annual temperature and rainfall variance present a small marginal effect on land use in all years, once results do not substantially differ across climate variability scenarios. Although cropland presents the greater percentage losses, the absolute area loss is greater for forest. For example, the average farm will reallocate 14.5 hectares of forest and 3.5 hectares of cropland into pastures in 2085 if climate variability increases in 10%.

Table 6. Projected land uses and percentage effects of climate change on the average BLA representative farm related to 2006

	No increase in climate variability		5% increase in climate variability		10% increase in climate variability	
	Land use (ha)	% variation	Land use (ha)	% variation	Land use (ha)	% variation
2025						
Cropland	12.74	-19.87	12.80	-19.52	12.85	-19.18
Pasture	120.33	11.74	121.05	12.41	121.77	13.07
Forest	80.44	-10.55	79.67	-11.40	78.90	-12.26
2055						
Cropland	13.31	-16.33	13.36	-15.99	13.42	-15.64
Pasture	118.08	9.65	118.80	10.32	119.52	10.98
Forest	82.13	-8.67	81.36	-9.53	80.59	-10.39
2085						
Cropland	11.52	-27.57	11.57	-27.23	11.63	-26.89
Pasture	125.24	16.29	125.95	16.96	126.67	17.63
Forest	76.76	-14.64	75.99	-15.50	75.22	-16.35

The impact of climate change is heterogeneous among BLA states (Table 7). In Amazonas, Acre, Amapá, Pará, Rondônia, Roraima, and Tocantins, land allocated in cropland presents a greater percentage decrease than forest in all years and variability scenarios. In Maranhão, the percentage decrease in forest is greater than the decrease in cropland because the average farm in this state allocates about 22 hectares in forest. This relative low allocation in forest leads to an expressive percentage change. Unlike the overall results for BLA, percentage changes in 2055 are greater than in 2025 in Amazonas, Acre, Amapá and Rondônia. This is due to the fact that expected rainfall variation in the second period is greater than in the first. Overall, qualitative results for BLA representative farm do not differ from representative farms in Amazonas, Acre, Amapá, Maranhão, Pará, Rondônia, Roraima and Tocantins. Compared to baseline, there will be less land allocated in crops and forest, and more land allocated in pasture in all scenarios. Furthermore, increase in climate variability has small marginal effects on land allocation in each of these states.

Table 7. Percentage effects of climate change on the average state representative farms

	No increase in climate variability			5% increase in climate variability			10% increase in climate variability		
	Cropland	Pasture	Forest	Cropland	Pasture	Forest	Cropland	Pasture	Forest
Amazonas and Acre[a]									
2025	-28.62	33.85	-13.80	-29.02	35.09	-14.41	-29.42	36.34	-15.02
2055	-30.06	35.55	-14.49	-30.46	36.79	-15.10	-30.86	38.04	-15.72
2085	-57.60	68.12	-27.77	-58.00	69.36	-28.38	-58.40	70.61	-28.99
Amapá									
2025	-49.41	26.71	-24.70	-53.40	29.67	-27.68	-57.39	32.62	-30.66
2055	-50.35	27.22	-25.17	-54.34	30.18	-28.15	-58.33	33.13	-31.13
2085	-62.43	33.75	-31.21	-66.42	36.71	-34.19	-70.42	39.67	-37.17
Maranhão									
2025	-31.17	34.42	-51.38	-31.28	35.59	-53.67	-31.39	36.77	-55.95
2055	-27.23	30.06	-44.88	-27.34	31.24	-47.17	-27.45	32.42	-49.45
2085	-38.48	42.48	-63.42	-38.59	43.66	-65.70	-38.70	44.84	-67.99
Mato Grosso									
2025	-1.03	0.60	-0.44	0.15	0.96	-0.97	1.32	1.32	-1.49
2055	1.04	-0.60	0.45	2.21	-0.24	-0.08	3.38	0.12	-0.61
2085	-4.46	2.59	-1.92	-3.29	2.95	-2.44	-2.12	3.32	-2.97
Pará									
2025	-44.41	19.16	-21.25	-45.20	20.09	-22.50	-45.99	21.03	-23.76
2055	-37.56	16.21	-17.97	-38.35	17.14	-19.23	-39.14	18.07	-20.48
2085	-54.01	23.31	-25.85	-54.80	24.24	-27.10	-55.59	25.17	-28.35
Rondônia									
2025	-33.66	12.65	-15.38	-33.58	13.06	-16.06	-33.50	13.47	-16.74
2055	-46.15	17.34	-21.09	-46.08	17.75	-21.77	-46.00	18.16	-22.45
2085	-80.71	30.32	-36.89	-80.63	30.74	-37.57	-80.55	31.15	-38.25
Roraima									
2025	-42.43	22.72	-15.60	-45.47	24.95	-17.27	-48.50	27.18	-18.94
2055	-40.29	21.57	-14.82	-43.33	23.80	-16.49	-46.36	26.03	-18.16
2085	-60.94	32.63	-22.41	-63.98	34.86	-24.08	-67.01	37.09	-25.75
Tocantins									
2025	-39.59	13.60	-17.34	-39.31	14.28	-18.54	-39.03	14.96	-19.73
2055	-22.04	7.57	-9.66	-21.76	8.25	-10.85	-21.48	8.93	-12.05
2080	-30.49	10.48	-13.36	-30.21	11.16	-14.55	-29.93	11.84	-15.75

a. The averaged representative farms in the state of Acre allocates a lower amount of land allocated in cropland (2.6 ha). To avoid negative allocation in cropland, we aggregated Acre with its limiting state Amazonas.

Results for Mato Grosso differ from other states in BLA. First, this state exhibits smaller percentage changes compared to other states. The State representative farm is quite larger than regional average, 586 hectares. This representative farm is divided into 39 hectares of cropland, 272 in pasture, and 275 in forest. Thus, any change in land allocations leads to a small percentage variation. Second, Mato Grosso presents a different pattern of rainfall change. Rainfall decreases in 34 mm and 148 mm in 2025 and 2085 compared to baseline. However, rainfall increases in 34 mm in 2055. This leads to an increase in cropland area and a decrease in pasture in all simulations for 2055. Third, the increases in climate variability changes the signs of cropland variations in 2025, and pasture and forest variations in 2055. Thus, there is no overall tendency in these periods. Notwithstanding, qualitative results for 2085 do not differ from other states. There will be more pasture and less cropland and forest in Mato Grosso in 2085 in any climate variability scenario.

2.5.Conclusion

This chapter developed a risk-averse land use model to estimate the effects of climate change on land use in BLA farms. Our findings suggest that rainfall, inter-annual temperature and rainfall variance affect land use decisions in BLA. Furthermore, there is evidence that farmers are risk-averse and cattle production is a less risky activity, once an increase in climate risk related to rainfall is positively related to land allocation in pasture. Thus, land allocation in pasture could be interpreted as a hedging strategy, explaining why farmers perform a low profit activity such as cattle production. Therefore, any policy seeking to improve agricultural yields in BLA should take into account that farmers are risk-averse. For instance, agricultural insurance could divert land from pasture to other uses. Furthermore, fixed payments for environmental services related to private forest could present a hedging effect, increasing land allocation in forests. Farmers will prefer to receive a guaranteed revenue from forest instead of performing a riskier activity like crop and cattle production. However, we cannot draw quantitative conclusion regarding risk-aversion, once we are unable to provide its actual extent by a structural parameter.

Simulations suggest that the average farmer's adaptation strategies are cropland and forest conversion into pasture. Depending on the increase in climate variability and time horizon, deforestation ratios range between 10% to 16% of total forest areas. The extent of forest conversion is greater in States within Amazon biome, such as Acre, Amazonas, Rondônia, Pará, and Rondônia. This will reduce biodiversity and environmental services form Amazon forest and increase GHG emissions. Therefore, policymakers should reinforce monitoring and control activities regarding land use regulation and deforestation in BLA. The decrease in cropland will reduce agricultural output, once agriculture presents a higher yield compared to cattle production. Once more, we could not quantify this latter impact, once there is no data on farm's profits and outputs to estimate all structural parameters.

Risk-neutral specification underestimates deforestation variations, as an increase in inter-annual rainfall variability fosters deforestation. For instance, accounting for inter-annual climate variability offset the impacts of rainfall variation in Mato Grosso. Therefore, future studies should rely on climate variability projections instead of our comparative static analysis. This may allow the simulation of the most probable scenario regarding climate variability.

Overall, climate change will probably be a source of land use change in the future. Therefore, there is a need for policies to avoid the conversion of forest into pastures in Brazilian Legal Amazon. Land use planning and zoning could play an important role as command and control policies.

3. Farm Size and Land Use Efficiency in Brazilian Amazon

3.1.Introduction

Providing food to the growing world population – while minimizing the impacts on the environment – is a challenging task for policymakers. Population is expected to increase in 2-billion over the next four decades which together with rapid urbanization and rising incomes should increase food demand in 60% compared to the current level (FAO 2013). Supply side responses to the growing food demand can trigger a process of land use change in which agricultural land replaces native vegetation. This can have harmful effects on the provision of ecosystem services as it can affect hydrological cycles, soil conservation, climate change, and biodiversity (Rudel et al. 2005; Rudel, Schneider, and Uriarte 2010). Increases in land productivity are essential to avoid further deforestation and accommodate increasing food demand and forest conservation.

In this chapter, we investigate the impact of farm size on land productivity in Brazilian Legal Amazon (BLA). Since Sen's (1962, 1966) seminal papers, the stylized fact of an inverse relationship between farm size and productivity is relatively well-established in developing country agriculture (Henderson 2015). The main explanations of this inverse relationship rely on labor markets failures, where labor effectiveness decreases as farm size increases (Barrett, Bellemare, and Hou 2010). Thus, as small farms are more productive than larger farms, land redistribution could increase agricultural production and decrease the need for new areas. Furthermore, land redistribution could also reduce income inequality in developing world. Despite the above-mentioned consensus, recent studies found that the inverse relationship between farm size and productivity does not hold to Brazil (Freitas 2014; Helfand and Levine 2004; Oliveira 2013).

Brazilian Legal Amazon (BLA)[27] is an appealing study case regarding the rational use of land for several reasons. First, Brazil has become a major player in the world agricultural market, being the fourth producer and exporter of agricultural products nowadays (FAO 2015). Second, this position is a result of an increasing agricultural production since 1970s, which is associated to a process of land use conversion from natural vegetation to agriculture as well as to a process of technological progress. A substantial share of this land conversion took place within BLA, with average deforestation rate of 15,000 km^2 over the last two decades (INPE 2015). Thus, Brazil ranked first in deforested area during 1990s and 2000s (FAO 2010). Third, land in BLA is concentrated in large farms. About 60% of the agricultural land is concentrated in farms with more than 1000 hectares in 2006 (IBGE 2014). These large farms account for 2.4% of the number of farms in BLA. In turn, only 1.33% of the agricultural area belongs to farms with less than 10 hectares. Furthermore, the number of small farms has decreased since 1980s. For instance, 55.6% of farmers in 1985 had less than 10 hectares, while this share was 35.27% in 2006. Thus, there has been land concentration in BLA over the time.

Some studies argues that smallholding agriculture has contributed less to deforestation is some BLA locations (Pacheco 2009; Ludewigs et al. 2009). Other found that smaller farmers in BLA are likely to deforest a higher proportion of their

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[27] BLA is a socio-economic region within Brazil created in 1950s for political purposes. It spans for nine states, covers 61% of Brazilian territory and is slight smaller than Europe. The 4 million km^2 of Brazilian Amazon lies within the 5.2 million km^2 of Brazilian Legal Amazon, the remaining is mostly cerrado biome (Homma 2008; SUDAM 2010).

area than larger establishments (Féres and Araujo 2013). Other analyzed the relationship of agrarian structure and technical/economic efficiency. Otsuki, Hardie, and Reis (2002) found that farms facing well-defined property rights are more efficient, leading to less deforestation. In a study of the Brazilian Midwest, an overlapped region with BLA, Helfand and Levine (2004) identified that technical efficiency presents a quadratic “U” shaped relationship with farm size. Therefore, as farm size increases, technical efficiency decreases until reaching a minimum when farm size is about 1000-2000 ha. After that, technical efficiency becomes an increasing function of farm size. Marchand (2012) investigated the relation between technical efficiency and deforestation in BLA. He found a “U” shaped effect of technical efficiency on deforestation – i.e. less and more efficient farms convert more forest into agricultural land than average efficient farms.

However, these studies fail in measuring the amount of land waste (i.e. the surplus of land used in agricultural production), as they use traditional measures of efficiency such as technical and economic efficiency. For instance, Otsuki, Hardie, and Reis (2002) argued that economic inefficient farms in BLA deforest more than efficient ones. However, they did not provide information on the amount of land that can be spared. Thus, applying technical efficiency methods could lead to a misleading conclusion regarding land efficiency, as this indicator could be associated to a misuse of other inputs than agricultural land. In turn, Marchand (2012) stated that deforestation is a measure of environmental efficiency, which could also be a misleading assumption. Reinhard, Lovell, and Thijssen (1999, 2000, 2002) and Reinhard and Thijssen (2000) demonstrated that environmental efficiency related to inputs is a relative rather than an absolute measure such as deforestation. If land is the strategic environmental input in BLA, environmental efficiency is the ratio between the minimum feasible land use to observed land use, keeping technology and observed levels of other inputs and output. In this chapter, we undertake a non-radial approach proposed by Reinhard, Lovell, and Thijssen (1999, 2002) to overcome the above-mentioned drawback and measure land use efficiency. This method allows gauging a single input technical efficiency for a firm using multiple inputs, being useful to measure waste of natural resources. For example, Karagiannis, Tzouvelekas, and Xepapadeas (2003) used this approach to measure water waste in a sample of Greek irrigated farms.

Therefore, we aim to analyze the relation between farm size and productivity in Brazilian Amazon. We adopt two alternative measures of productivity: an input-oriented land use efficiency and an output-oriented technical efficiency. These two efficiency measures provide information about how farm-size is associated to land waste and overall input wastes, providing different policy insights. Land use efficiency relates to the amount of land that could be spared while producing the same output quantity, whilst technical efficiency is associated to the potential increase in output. Therefore, our study presents two analysis regarding the current process of land concentration BLA: the impact on land waste and agricultural production.

This chapter is organized as follows: Section 3.2 briefly describes the main theoretical insights regarding the inverse relation between farm-size and productivity; Section 3.3 presents the empirical strategy and describes the database; Section 3.4 presents the estimated results; and Section 3.5 consolidates the main conclusions and points out the policy analysis implications.

3.2.The Relationship between Farm Size and Productivity

The issue of farm size and land productivity has received a great deal of attention by the rural development literature. The pioneering analyses date back to the 1920s, when Chayanov noted an inverse relation between farm size and productivity during the first years of Soviet Union (J. J. Assunção and Braido 2007; Barrett, Bellemare, and Hou 2010). Nowadays, there is a relative consensus that such inverse relation is explained by market failures. Such failures prevent the market to converge to its competitive equilibrium, in which low-productivity farmers would lease or sell land to high-productivity farmers (J. J. Assunção and Braido 2007; Barrett, Bellemare, and Hou 2010). The most frequent market failures in this literature relate to dual labor market, risk aversion and supervision of hired labor.

Sen's (1962, 1966) notion of dual labor market is the first appealing baseline to explain the inverse relationship between farm size and productivity in developing countries. This framework consists in segmented labor allocation behavior between market-oriented farmers and subsistence-oriented peasants. The market-oriented farmer behaves under the traditional production maximization assumption, equalizing marginal productivity with wages. The peasant family, instead, allocates labor to maximize its subsistence, resulting in a surplus labor compared to a market equilibrium. Thus, a subsistence-oriented farmer allocates more labor per unit of land than a market-oriented one. This may occur in rural areas where unpaid-family workers supply labor, there are few job opportunities, and peasants face a lower opportunity cost of labor. These two types of farms are polar cases and hybrid intermediate cases may occur in developing countries. Sen (1966) pointed out that the proportion of market-oriented farms increases with farm size. This may lead to inverse relationship between size and productivity.

Srinivasan (1972) showed that under risk-aversion and yield risk related to weather, it is optimal for a small farmer to apply more inputs per area than for a large one. Barrett (1996) highlighted the role of price risk on the inverse farm size-productivity relationship. The author observed that if farmers are risk-averse and agricultural insurance markets are absent, net buyer farmers would over-supply labor in agricultural production to avoid food scarcity related to price fluctuations in the market (i.e. reduce their market dependence). In turn, net seller farmers would under-supply labor to reduce their exposure to price fluctuations in the market. Since households in smaller farms are likely to be net buyers whilst those in lager farms are likely to be net sellers, the inverse relationship arises again.

Another explanation to the inverse relationship between farm size and productivity relies on a principal-agent problem related to hired labor (Bardhan 1973; Eswaran and Kotwal 1986; Feder 1985). According to this approach, effectiveness – or efforts – of hired workers are positively associated to supervision of family workers and to the farm size. Family workers always exert the maximum effort. The greater is the proportion of family workers, the greater is the effort exerted by hired workers. Furthermore, effectiveness of family supervision of hired workers decays with farm size. Larger farms are likely to have a small proportion of family works than smaller farms. Thus, moral hazard issues would provide a possible explanation the inverse farm size-productivity relationship.

3.3.Empirical Strategy

Most of the literature on farm size and land productivity in developing countries consider yields as proxy for productivity. However, Barrett (1996) observed that yields are a partial productivity measure, since it does not account for the use of other inputs. In fact, Fried, Lovell, and Schmidt (2008) pointed out that overall productivity is broadly determined by four components: production technology, scale of operation, operating efficiency, and the environment in which production occurs. Technology and scale effects on productivity are associated to the "shape" of the production function, which we presume to be identical across farmers. The environmental component is a random variable exogenous to the farmer. The efficiency component is a measure of the "distance" from the observed production to the best production possibility. This latter component could be interpreted as agents' "managerial skills" and it corresponds to a performance index. Thus, efficiency measures are best suitable to assess how market failures in the previous section affect agricultural performance. For example, if we use yields instead of an efficiency measure, the inverse farm size/productivity relation could arise due to decreasing returns to scale. This may not reflect the role of market failures in the inverse relationship. We assume that market failures affect the "managerial skill", especially in labor effectiveness.

In our empirical application, we use two measures of efficiency: Technical Efficiency (TE) and Land Use Efficiency (LUE). TE is a measure of efficiency related to a best practice frontier. This measure may be interpreted in terms of input-oriented and output-oriented projections. The first relates to the overall excess of input used in production and the second are the rate of potential to observed production. As we are interested in measuring the surplus of land used in agriculture, we adopt the input-oriented approach in order to construct out LUE indicator.

Figure 1 presents a frontier isoquant for a given level of aggregated agricultural production Y_R. A farmer producing Y_R with input quantity R is out of the frontier. This farmer is technically inefficient, once he/she could produce the same amount of output by using input quantity B at the frontier.

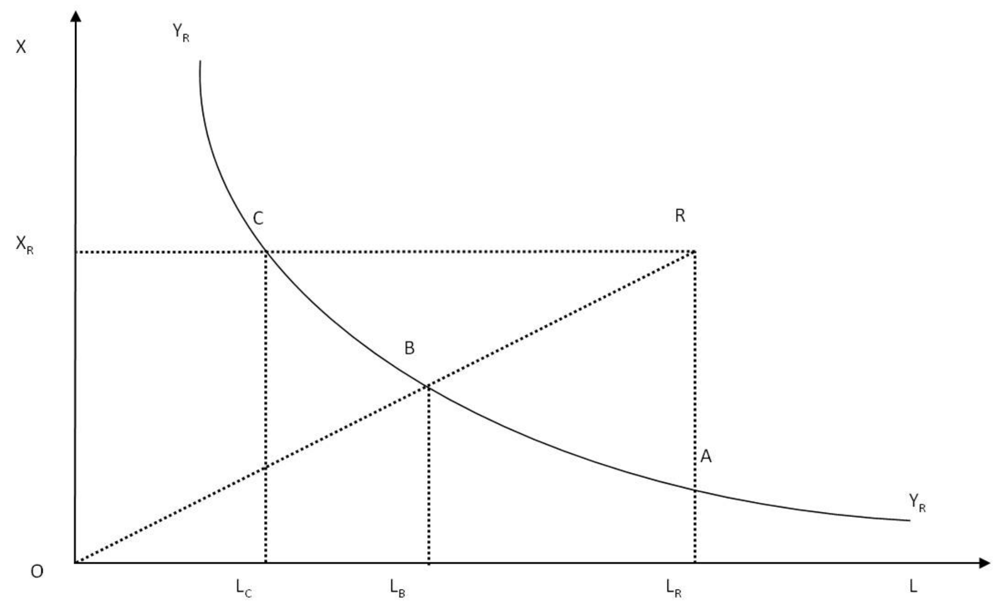

Figure 1. Production frontier for general input X, and land input (L).

LUE measures the amount of land each farm is being wasted related to the best practice frontier. Reinhard, Lovell, and Thijssen (1999) built a non-radial measure to represent the amount of waste from a single input[28]. This measure consists in reducing the amount of a single input of interest (land in our analysis) while keeping the amount of other inputs and the production constant. A farmer producing an output Y_R by using an input quantity R is wasting land (L) as well as other inputs (X). This farmer could reduce the amount of land until reach the isoquant Y_R and use input quantity C. Thus, one can express LUE as

[28] Reinhard, Lovell, and Thijssen (1999) created this measure to account for detrimental inputs. We adapted their approach to account for land surplus in agriculture.

$$LUE = \min\left[\theta : F\left(X_R, \theta L_R\right) \geq Y_R\right] = \left|OL_C\right| / \left|OL_R\right| \tag{15}$$

where θ is the score of LUE; and L_R is the minimum feasible use of land, given the best practice production function $F(\bullet)$ and the observed values of output Y_R and conventional inputs X_R.

A technical efficient farmer is also land use efficient, as he/she is at the frontier. However, as Reinhard, Lovell, and Thijssen (1999) pointed out, these two measures may not be the same when farmers are not technical efficient.

We are also interested in a measure of TE to compare with LUE results and test the inverse relation. An output-oriented TE measure for a single input is illustrated Figure 2. A farmer using input X_R and producing Y_R is inefficient. He/she could increase output to Y^F at the frontier using the same amount of input X. Thus, one could express TE as

$$TE = \left\{\max\left[\phi : \phi Y_r \leq F\left(X_r\right)\right]\right\}^{-1} = \left|OY_R\right| / \left|OY^F\right| \tag{16}$$

where ϕ is the score of $F(\bullet)$ is a production function at the frontier, representing the best practice regarding the use of a given inputs vector X_r; and Y_r is the observed value of output.

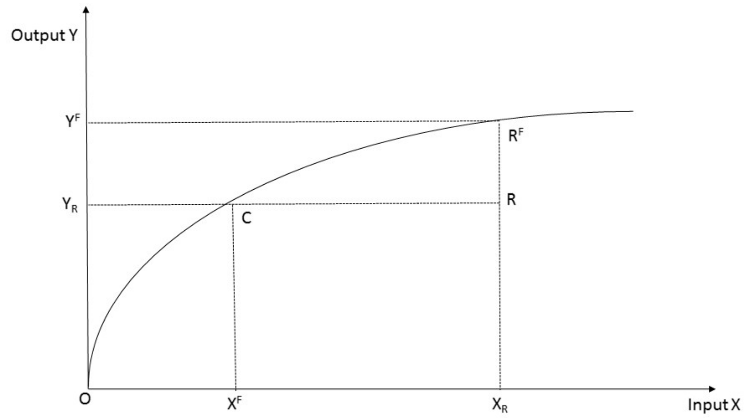

Figure 2. Production frontier in output (Y) and a single input (X).

3.3.1. TE and LUE Estimation

There are several approaches to estimating an efficiency index (Kalirajan and Shand 1999; Murillo-Zamorano 2004). In our empirical application, we adopt the Stochastic Frontier Analysis (SFA) (Aigner, Lovell, and Schmidt 1977; Meeusen and Van den Broeck 1977). SFA is a parametric technique with some advantages over other parametric and non-parametric techniques. First, it accounts for random variables such as weather and pests in agriculture production. Second, it presents the estimation of the production frontier, rather than a linear approximation. These two features make SFA preferable to alternative approaches like Data Envelopment Analysis (DEA). The latter do not consider the role of random variables. Not considering random variables, a farmer would appear to be inefficient if he/she faces harmful weather conditions and not because of a managerial deficit. Furthermore, the frontier in DEA is a piecewise linear approximation of the true frontier. Thus, this procedure tends to overstate efficiency scores and the number of efficient observations.

In fact, Bravo-Ureta et al. (2007) found that DEA produces greater efficiency scores than SFA in empirical studies.

According to Greene (2008), a Maximum Likelihood estimation of a production frontier can be derived from the following expression

$$Y_i = F(L_i, X_i; \beta) \times \exp\{V_i - U_i\} \qquad (17)$$

where Y_i is the aggregated output produced by farm i; L_i is the amount of agricultural land; X_i is a vector of inputs quantities; β is a vector of estimated parameters; V_i is the error term, independently and identically distributed as $N(0, \sigma_v^2)$; U_i is a nonnegative error term, independently and identically distributed, that measures (output-oriented) TE. We consider that U_i presents the half-normal or an exponential distribution.

Rearranging (17), one could express TE as

$$TE = \frac{Y_i}{F(L_i, X_i; \beta) \times \exp\{V_i\}} = \exp\{-U_i\} \qquad (18)$$

If $U_i \geq 0$, thus $0 < \exp\{-U_i\} \leq 1$. When $\exp\{-U_i\} < 1$, the farm is below the frontier (i.e. is inefficient). If $\exp\{-U_i\} = 1$, the farm is efficient and lies at the frontier. We chose the TE estimator proposed by Battese and Coelli (1988). According to Murillo-Zamorano (2004, 49), this estimator is preferred to alternative approaches when U_i is not close to zero

We parametrize $F(\bullet)$ by using a translog specification

$$\ln Y_i = \beta_0 + \sum_k \beta_k \ln X_{ik} + \beta_L \ln L_i + \frac{1}{2}\sum_k \sum_r \beta_{kr} \ln X_{ik} \ln X_{ir} + \sum_k \beta_{Lk} \ln L_i \ln X_{ik} + \frac{1}{2}\sum_k \sum_r \beta_{LL} (\ln L_i)^2 + V_i - U_i \tag{19}$$

The translog specification is characterized as a flexible functional form, since the elasticity of substitution may vary across inputs. It is a continuous and twice differentiable function and monotonicity is verified locally. The specification also assumes symmetry in parameter for interacted variables ($\beta_{kr} = \beta_{rk}$).

A farmer is technically efficient if $U_i = 0$ in expression (19). Thus, one can express the production function of an efficient farm as

$$\ln Y_i = \beta_0 + \sum_k \beta_k \ln X_{ik} + \beta_L \ln L_i^F + \frac{1}{2}\sum_k \sum_r \beta_{kr} \ln X_{ik} \ln X_{ir} + \sum_k \beta_{Lk} \ln L_i^F \ln X_{ik} + \frac{1}{2}\sum_k \sum_r \beta_{LL} \left(\ln L_i^F\right)^2 + V_i \tag{20}$$

Assuming that $\ln LUE = \ln L_i^F - \ln L_i$, and equalizing expressions (19) and (20), Reinhard, Lovell, and Thijssen (1999) showed that

$$\ln LUE = \left(-\varepsilon_L \pm \sqrt{\varepsilon_L{}^2 - 2\beta_{LL} U_i}\right) \Big/ \beta_{LL} \tag{21}$$

where ε_L is the output elasticity with respect to land, which is expressed as $\partial \ln Y_i / \partial \ln L_i = \beta_L + \sum_k \beta_{Lk} \ln X_{ik} + \beta_{LL} \ln L_i$.

LUE score is calculated by the antilog of expression (21) using the positive square root. Reinhard, Lovell, and Thijssen (1999) explained that the technical efficient farm is also land use efficient. Hence, $U_i = 0 \Rightarrow \ln LUE = 0$ only if we consider the positive square root. It is noteworthy that $\ln LUE$ exists only if $\beta_{LL} < 0$ or $\beta_{LL} > 0$ and $|\varepsilon_L|$ is sufficiently large (Reinhard, Lovell, and Thijssen 1999).

3.3.2. Explaining LUE and TE

The so-called "second-stage" of efficiency analysis allows identifying the sources of efficiency. Kumbhakar and Lovell (2003) highlighted that this stage is important to capture the role of exogenous variables on production other than the inputs. These sources are associated to managerial skills, land tenure, competitive pressure, information availability, input quality, etc. In our study, the theoretical framework in section 3.2 assumes that farm-size is associated to labor input quality, information availability and managerial skills.

We adopt the approach proposed by Reinhard, Lovell, and Thijssen (2002) to obtain the relationship between farm-size and LUE, that consists in the ML estimation of the following stochastic frontier in the second-stage

$$\ln LUE_i = H(Z_i;\gamma).\exp\{V_i^* - U_i^*\} \quad (22)$$

where z_i is the exogenous variables related to farm i that explain LUE; γ is a vector of parameters; V_i^* is the error term, independently and identically distributed as $N(0,\sigma_{v*}^2)$; U_i^* is a nonnegative error term, independently and identically distributed, which is a (residual) measure of LUE.

The approach proposed by Reinhard, Lovell, and Thijssen (2002) presents advantages to alternative estimation methods. First, alternative methods assume that exogenous variables explain all efficiency heterogeneity among firms. Reinhard, Lovell, and Thijssen (2002) argue that the exogenous variables partly explain efficiency, and their proposed approach provides a better economic intuitive explanation. Expression (22) provides parameters estimates related to a function of explanatory variables observed by the analyst. Notwithstanding, it is likely to remain inefficiencies related to unobserved factors. These factors are represented in U_i^*. Second, Reinhard, Lovell, and Thijssen (2002) procedure is better from a statistical perspective, once it provides better estimations for the second-stage in presence of a composite error term $V_i^* - U_i^*$. For example, OLS estimates are biased and inconsistent if the real disturbance term are $V_i^* - U_i^*$ instead of V_i^*.

The main approach to explain technical efficiency is the estimation of a second-stage similar to expression (22), where U_i is regressed on the exogenous variables z_i. However, some studies pointed out that this procedure is inappropriate because U_i is an independent and identically distributed variable (Battese and Coelli 1995; Fried, Lovell, and Schmidt 2008). Hence, parameter estimates of exogenous variables are inconsistent[29].

To overcome above-mentioned drawback, Fried, Lovell, and Schmidt (2008) suggested that the equation of TE determinants should be estimated jointly with the

[29] It should be remarked that this is not a problem to estimate the sources of $\ln LUE$ in (22), as it is calculated from estimated parameters that describes the structure technology and the one-sided error component (Karagiannis, Tzouvelekas, and Xepapadeas 2003; Reinhard, Lovell, and Thijssen 2002).

production function in a single-stage framework. They proposed the following estimation procedure by ML

$$Y_i = F(L_i, X_i; \beta) \times \exp\{V_i - U_i(Z_i; \alpha)\} \qquad (23)$$

where $F(\bullet)$ is the translog given (19); Z_i is the vector of exogenous variables that explain technical inefficiency; and α is a vector of parameters. According to Fried, Lovell and Schmidt (2008), such procedure ensures consistent estimations. To deal with potential spatial autocorrelation, we bootstrap the errors in (17), (22), and (23) with 100 replications clustered by municipality.

3.3.3. Variables and Data

Most of our data come from Brazilian Agricultural Census of 2006 provided by the Brazilian Institute of Geographic and Statistics (*Instituto Brasileiro de Geografia e Estatística* – IBGE). IBGE provides Agricultural Census data on municipal level segmented into five land tenure groups (owner, sharecropper, renter, occupant and farmers recently granted in land reform (less than five years)) and eleven farm-size groups. We created representative farms from averages of each group formed from a municipality “i”, land tenure “j” and farm size group “k”. Thus, each municipality could present up to 55 of these representative farms.

Output is measured by the value of agricultural production expressed in Brazilian currency (real R$). We construct this variable as a residual procedure, by subtracting the value of extractive, forestry and rural industry production from total production value. As extractive and forestry products are from stand forest and rural industry uses less land than agricultural production, we assume that the output variable measures the production that takes place in deforested areas in BLA.

We consider that farmers in BLA use three fixed inputs: agricultural land, labor and capital. Agricultural land is the total area of the representative farm less areas with buildings, covered with water, unsuitable to agriculture, natural forests, and planted forests. The proxy for labor is a variable created by IBGE that corresponds to an adult working eight hours per day, 260 days per year. Capital is the declared value in *reais* of machines and improvements (mainly buildings).

Some variables in the second-stage are also extracted from the 2006 Agricultural Census. Farm-size is the area of the establishment, including agricultural land, forests, buildings, covered with water, and unsuitable to agriculture. As our observations refer to a single year, we add some variables to control heterogeneity among representative farms. The first set of controls is dummy variables representing the tenure structure groups: owners, sharecropper, renter, occupant and farmers recently granted in land reform. The second set of variables refers to output composition. We calculated the share of output value related to cattle, permanent crops, temporary crops and other activities such as horticulture, dairy, poultry, etc. We excluded cattle proportion and expose results relative to this activity. The third set of control variables correspond to social and demographic-related characteristics. These are the proportion of farms within a group with the following features: managed by women, the manager is younger than 25, the manager is older than 55, the manager has more than ten years of experience in agriculture, the manager studied less than eight years.

To control for institutions, we used a dataset provided by Catholic Pastoral Land Commission for 2005. These variables include the number of rural conflicts per municipality, the number of murders and murders attempts related to land per municipality and the number of farms caught with slavery and poor work conditions per municipality. Finally, the last set of variables represents agronomic features such as soil, topography, and latitude. The first two variables are the percentage of the municipality area covered by eight soil and five topography classes. These classes range to less suitable to more suitable to agriculture. The reference for soil is soil class 1 and the reference for topography is topography class 2[30]. Soil and topography data were provided by Center for Studies and Spatial Systemic Models (*Núcleo de Estudos e Modelos Espaciais Sistêmicos* - NEMESIS). The variable latitude controls for the incidence of solar radiation and other geographic related factors. This variable is the absolute latitude of municipalities centroids provided by IBGE.

After discarding missing values, our data set covered 1,287,358 farms aggregated into 5564 representative farms. Table 8 presents the descriptive statistics of variables. We applied the natural logarithm to output and input variables to estimate the translog production function. We add quadratic term to farm-size in efficiency equations to capture non-linearities.

[30] We did not use topography 1 in estimations because it is rare class within Amazon, which could lead to multicolinearity.

Table 8. Descriptive statistics of variables of interest in BLA

	mean	sd	cv	min	max
Output	37725.81	601516.93	15.94	3.32	26677700.00
Land	148.87	737.54	4.95	0.00	17544.00
Labor	1.40	2.95	2.11	0.74	121.80
Capital	74486.60	628561.13	8.44	0.91	24680400.00
Size	256.66	1355.48	5.28	0.01	33329.83
Owner	0.79	0.41	0.52	0.00	1.00
Settled	0.10	0.29	3.08	0.00	1.00
Renter	0.02	0.14	6.85	0.00	1.00
Sharecropper	0.01	0.10	10.30	0.00	1.00
Occupant	0.09	0.28	3.27	0.00	1.00
Cattle	0.35	0.31	0.89	0.00	1.00
Permanent crops	0.09	0.19	2.13	0.00	1.00
Temporary crops	0.29	0.31	1.05	0.00	1.00
Other	0.26	0.28	1.08	0.00	1.00
Education	0.30	0.11	0.35	0.00	1.00
Experience	0.19	0.10	0.55	0.00	1.00
Woman	0.03	0.04	1.04	0.00	0.40
Young than 25	0.01	0.02	1.54	0.00	0.40
Older than 55	0.13	0.08	0.57	0.00	1.00
Conflicts	0.76	1.75	2.30	0.00	15.00
Slavery/Poor work conditions	0.61	2.06	3.36	0.00	20.00
Murder/Attempts	0.08	0.47	5.76	0.00	5.00
Latitude	8.31	4.43	0.53	0.03	17.83
% soil type 1	5.43	18.25	3.36	0.00	100.00
% soil type 2	4.28	17.26	4.03	0.00	100.00
% soil type 3	2.74	12.74	4.65	0.00	100.00
% soil type 4	45.79	38.85	0.85	0.00	100.00
% soil type 5	1.80	10.92	6.08	0.00	99.42
% soil type 6	4.76	17.35	3.65	0.00	100.00
% soil type 7	0.43	4.23	9.92	0.00	72.04
% soil type 8	34.77	37.96	1.09	0.00	100.00
% topography type 2	34.77	37.96	1.09	0.00	100.00
% topography type 3	4.35	16.99	3.90	0.00	100.00
% topography type 4	58.71	38.17	0.65	0.00	100.00
% topography type 5	1.75	10.91	6.22	0.00	99.42

sd – standard deviations; cv – coefficient of variation; min – minimum; max – maximum.

3.4.Results

Results of the first-stage are presented in Table 9. Specifications differ according to the statistical distribution assumed for TE (Half-normal and Exponential) and the presence of state-level dummies. The translog functions in Table 9 differ from the proposed specification in expression (20). The coefficient of land squared was not significant at 10% when we estimated the full translog specification as in (20) (i.e. with inputs interactions)[31]. This coefficient is a necessary condition to calculate land use efficiency. Thus, we opted to the specification in Table 9 in order to enable the proposed analysis.

[31] See Table A8 in appendix.

Table 9. Estimation of technical efficiency with special case of translog production function for BLA in 2006

	(1)	(2)	(3)	(4)
Land	0.129***	0.141***	0.127***	0.138***
	(0.0132)	(0.0163)	(0.0135)	(0.0137)
Labor	0.830***	0.813***	0.842***	0.823***
	(0.144)	(0.0872)	(0.144)	(0.149)
Capital	-0.297***	-0.289***	-0.346***	-0.344***
	(0.0918)	(0.107)	(0.108)	(0.105)
Land^2	-0.0317***	-0.0318***	-0.0311***	-0.0308***
	(0.00853)	(0.00968)	(0.00863)	(0.00862)
Labor^2	0.0390	0.0403	0.0309	0.0325
	(0.108)	(0.0685)	(0.104)	(0.104)
Capital^2	0.0694***	0.0672***	0.0755***	0.0741***
	(0.0121)	(0.0137)	(0.0142)	(0.0138)
Constant	7.478***	7.386***	7.997***	7.940***
	(0.354)	(0.465)	(0.505)	(0.481)
AIC	16500.8	16420.7	16497.7	16413.6
BIC	16560.4	16533.3	16557.3	16526.2
TE distribution	Half-normal	Half-normal	Exponential	Exponential
State FE	no	yes	no	yes
Lambda	0.00709	0.00599	0.342***	0.371***

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Coefficient estimates in Table 9 are quite robust, with little variation across the distinct specifications. Statistical significance of the lambda parameter in columns 3 and 4 indicates that exponential distribution captures the inefficiency in agricultural production in BLA. According to Aigner, Lovell and Schmidt (1977), lambda is the ratio of standard deviation of U_i and V_i. When lambda is statically different from zero, the inefficiency term U_i is relevant to explain agricultural production. In addition to that, bayesian (BIC) and Akaike (AIC) information criteria indicate that column 4 provides the most adequate specification. In what follows, we base our analysis on this specification.

Table 10 presents results regarding elasticities of production, returns to scale and technical and land use efficiencies. We build these indicators for each representative farm weighted by the number of observation within the group. Elasticities indicate that agricultural production in BLA is more sensitive to labor variations than capital and land. In average, 1% increase in land endowment will lead to a 0.08% increase in agricultural output. In general, land has low elasticities and about 7.3% of farms in BLA present negative elasticities of production, violating theoretical assumptions. Labor elasticity of production is constant in BLA, as coefficient of labor squared is not statistically significant at 10%. This higher value indicates that production in BLA would greatly increase if farmers allocate more labor units in production. Capital elasticity is negative for 2.5% of BLA farms. For the average farm, an increase in capital endowment in 1% leads to an increase in 0.26% in agricultural production. Summary statistics for returns to scale indicates that he average farm in BLA operates with increasing returns. In fact, about 95% of BLA farms present increasing returns to scale. Marchand (2012) also found increasing returns to scale in BLA utilizing data from 1995/1996 Brazilian Agricultural Census.

Table 10. Elasticities of production, returns to scale, technical and land use efficiencies in BLA[32]

	Mean	sd	min	max
Land	0.080	0.061	-0.163	0.391
Labor	0.823	0.000	0.823	0.823
Capital	0.259	0.120	-0.351	0.918
Returns to scale	1.162	0.091	0.543	1.658
TE	0.739	0.051	0.061	0.900
LUE	0.096	0.080	0.000	0.598

Table 10 also reports summary statistics for technical efficiency (TE) and land use efficiency (LUE). These two efficiency scores present a Spearman rank correlation of 0.3228 and the null hypothesis that theses efficiency scores are not correlated is rejected at 1%. Thus, the assumption that technical efficiency gauges land use waste

[32] We weighted summary statistics by the number of respondents. Alternative results for a full translog specification are in Table A9.

is somehow weak. Albeit the correlation is positive and significant, it has a low value. Therefore, Otsuki, Hardie, and Reis (2002) conclusions regarding efficiency and deforestation may not hold for BLA, as TE is not a good measure of land use waste.

Average technical efficiency means that the actual agricultural production in BLA represents 73.9% of its potential. This means that the average BLA farm could increase its agricultural production in 35.3% using the current amount of inputs. Land use efficiency is much lower than technical efficiency. The average LUE value means that BLA farmers could reduce agricultural land in 90.4% and produce the same output using the current amount of labor and capital. In general, studies using this methodology have found smaller values for non-radial efficiency (like LUE) compared to technical efficiency scores (Karagiannis, Tzouvelekas, and Xepapadeas 2003; Reinhard, Lovell, and Thijssen 1999). Nevertheless, our findings are quite low in comparison to literature. We attribute this low LUE to the also low land elasticity of production, which enters directly in LUE formula in expression (21). This finding partly agrees with Ferreira Filho, Ribera, and Horridge (2015) study for Brazil. Using a General Equilibrium model, these authors have found that the reduction of agricultural land related to a slowing or halt in deforestation would have a minimum negative impact on agriculture output growth in the period 2005-2025. They argued that the reduced land supply leads to an effective use of the existing land. Our results confirm their conclusion, as a great extent of land is far below its effective use in BLA.

The estimated relationship between farm-size and LUE is in Table 11. The results in Table 11 refer to land use inefficiency expressed in equation (22) ($-\ln LUE_i$). Thus, a variable that is positively associated to land use inefficiency is negatively associated to LUE. We proceed this way to compare results of LUE and TE sources, as the latter is by definition for technical inefficiency ($-U_i(Z_i;\alpha)$). We successively add group of controls in each column to check robustness of farm-size and LUE relationship. Column 1 considers only farm-size as explanatory variables. We add land tenure dummies in column 2, composition of output in column 3, demographic variables in column 4, institutions in column 5, and agronomic variables in column 6. We suppressed results for agronomic variables to save space. The coefficients of lambda are significant at 1% in all specifications. Thus, farm-size and controls are not sufficient to explain the whole land use inefficiency in BLA, and U_i^* is relevant to explain LUE. The results in Table 11 have exponential distribution for U_i^*, as it was the distribution utilized to calculate TE and LUE.

Overall, results for farm-size are robust to the six specifications. The coefficients on farm-size decay as we introduce controls. However, the signs and statistical significance do not change across specifications. Therefore, there is an inverse “U” relationship between farm-size and land use inefficiency. The farm-size at the point of maximum is about 16,400 hectares in all 6 specifications. For farm-size smaller that this number, land use inefficiency increases (LUE decreases) as farm-size increases. Land use inefficiency is a decreasing function of farm-size for values greater than 16,400 hectares. For policy analysis purposes, results indicate that the prevailing farm-size/LUE relationship is negative, as the bunch of farmers in BLA is far smaller than 16,000 hectares. Therefore, the current land concentration process will diminish LUE in BLA.

Table 11. Regression results for the sources of land use inefficiency in BLA

	(1)	(2)	(3)	(4)	(5)	(6)
Farm size						
Size	0.00334***	0.00320***	0.00332***	0.00293***	0.00292***	0.00290***
	(0.000275)	(0.000275)	(0.000234)	(0.000270)	(0.000268)	(0.000275)
Size^2	-1.02e-08***	-9.80e-08***	-9.98e-08***	-8.93e-08***	-8.90e-08***	-8.84e-08***
	(1.61e-08)	(1.58e-08)	(1.52e-08)	(1.51e-08)	(1.50e-08)	(1.51e-08)
Land tenure						
Settled		-0.247***	-0.238***	0.0412	0.0344	0.0269
		(0.0683)	(0.0639)	(0.0727)	(0.0725)	(0.0720)
Renter		-0.0580	0.238	0.280	0.267	0.244
		(0.362)	(0.314)	(0.282)	(0.256)	(0.253)
Sharecropper		-1.217***	-0.424***	-0.308***	-0.295***	-0.269***
		(0.0992)	(0.0838)	(0.0876)	(0.0884)	(0.0899)
Occupant		-0.616***	-0.341***	-0.267***	-0.268***	-0.254***
		(0.0752)	(0.0653)	(0.0713)	(0.0709)	(0.0682)
Composition of output						
Permanent crops			-2.016***	-1.925***	-1.912***	-1.859***
			(0.0999)	(0.0918)	(0.0881)	(0.0933)
Temporary crops			-1.524***	-1.444***	-1.436***	-1.434***
			(0.0727)	(0.0678)	(0.0672)	(0.0708)
Other			-0.952***	-0.762***	-0.746***	-0.725***
			(0.107)	(0.104)	(0.101)	(0.109)
Demographics						
Education				-1.814***	-1.841***	-1.886***
				(0.293)	(0.291)	(0.306)
Experience				1.799***	1.859***	1.948***
				(0.260)	(0.269)	(0.285)
Women				-6.809***	-6.811***	-6.790***
				(0.692)	(0.695)	(0.704)
Younger than 25				4.223***	4.236***	4.404***
				(1.127)	(1.140)	(1.147)
Older than 55				1.153***	1.170***	0.948**
				(0.372)	(0.373)	(0.380)
Institutions						
Conflicts					0.0341**	0.0296**
					(0.0135)	(0.0135)
Slavery					0.0129	0.0104
					(0.0166)	(0.0184)
Murders					-0.0750	-0.0797
					(0.0599)	(0.0626)
Constant	3.659***	3.747***	4.546***	4.646***	4.606***	-37.66
	(0.0507)	(0.0547)	(0.0710)	(0.101)	(0.0935)	(65.61)
Lambda	0.885***	0.861***	0.952***	0.870***	0.869***	0.868***

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Coefficients for sharecroppers and occupant dummies decay substantially as we introduce controls. Nonetheless, their signs and statistical significance do not change. This land tenure classes are more land use efficient than owners. This is an unexpected result for occupant farmers and other studies have found a different relation. For instance, Mendelsohn's (1994) theoretical model pointed out that landowner without titles tend to perform a less sustainable economic activity than a titled owner. Otsuki, Hardie and Reis (2002) and Helfand and Levine (2004) found a negative relationship between occupant and technical efficiency. All classes of composition of output are more land use efficient than cattle. Farmers with higher education and farms managed by woman are more land use efficient. Manager experience is negatively associated to LUE. Older and younger farmers are less land use efficient than middle-aged farmers. Finally, farmers in municipalities with a higher incidence of rural conflicts present smaller LUE.

Results for TE efficiency are in Table 12 and were calculated using expression (23). We estimated six specifications to check coefficient robustness, as we proceed for LUE. Coefficients in the second equation explain technical inefficiency as we estimated the $-U_i(Z_i;\alpha)$ function. Thus, a negative sign indicates that a variable is positively associated to TE. Results for farm-size are again robust to specifications. There is an inverse "U" relationship between farm-size and technical inefficiency. The point of maximum is very close to the results for land use inefficiency, about 16,600 hectares. Thus, technical inefficiency is an increasing function of farm-size for values smaller than 16,600 hectares, and a decreasing function of farm-size for greater values. Notwithstanding, there is a negative relation between farm-size and TE for policy analysis purposes, as an increase in the present values of farm-size will lead to less agricultural production in BLA. Unlike the results for LUE, our results do not show a comprehensive relation between TE and other variables.

Table 12. Regression results for the sources of technical inefficiency in BLA

	(1)	(2)	(3)	(4)	(5)	(6)
Farm size						
Size	0.627***	0.625***	0.619***	0.602***	0.601***	0.579***
	(0.0626)	(0.0603)	(0.00236)	(0.0845)	(0.0842)	(0.00590)
Size^2	-1.88e-05***	-1.87e-05***	-1.86e-05***	-1.81e-05***	-1.80e-05***	-1.74e-05***
	(2.90e-06)	(2.84e-06)	(2.04e-06)	(3.34e-06)	(3.33e-06)	(1.90e-06)
Land tenure						
Settled		0.174	0.221	0.322*	0.249	-0.335
		(0.401)	(0.335)	(0.166)	(0.158)	(1.780)
Renter		0.0751	0.125	0.168*	0.155	-0.150
		(0.438)	(0.250)	(0.0934)	(0.0962)	(3.881)
Sharecropper		0.278	0.290**	0.261	0.304	1.688
		(0.254)	(0.114)	(0.180)	(0.199)	(2.402)
Occupant		0.241***	0.273***	0.266***	0.306***	0.424
		(0.0486)	(0.0581)	(0.0996)	(0.107)	(1.191)
Composition of output						
Permanent crops			0.221	0.336	0.344	0.506
			(0.279)	(0.804)	(0.827)	(1.695)
Temporary crops			0.0195	0.184	0.138	-0.428
			(0.487)	(0.654)	(0.652)	(1.090)
Other			0.184	0.244*	0.292**	1.037
			(0.201)	(0.128)	(0.137)	(0.747)
Demographics						
Education				0.295	0.167	-0.340
				(0.442)	(0.411)	(1.436)
Experience				-0.0393	-0.612	-5.509
				(1.211)	(1.182)	(4.803)
Women				0.856	1.428	7.111
				(1.303)	(1.475)	(6.703)
Younger than 25				-0.257	-0.584	-6.904
				(1.095)	(1.086)	(6.482)
Older than 55				0.0781	-0.371	-2.905
				(1.009)	(1.016)	(4.313)
Institutions						
Conflicts					0.131	-0.0563
					(0.103)	(0.295)
Slavery					0.106	-0.0594
					(0.128)	(0.427)
Murders					0.0461	0.107
					(0.242)	(1.554)
Constant	0.0353	0.0284	0.113	0.256*	0.189	-0.143
	(0.468)	(0.602)	(0.437)	(0.155)	(0.151)	(0.681)

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

3.5.Conclusion

This chapter investigated the relationship between farm size technical efficiency in Brazilian Legal Amazon. Our results indicate that TE is not a good indicator to gauge land waste in BLA. Thus, the statement that a lower TE fosters deforestation is not necessarily true. We also found that land is inefficiently used in BLA, and an expressive reduction in land would not necessary decrease agricultural production in the region. Hence, there is no need to convert forest into agricultural land to increase agricultural production in the future. Furthermore, the historically process of deforestation would be avoided if farmers used land in an efficient way in the region.

Our measures of productivity, TE and LUE, presented a nonlinear relationship with farm size. However, we did not rule out the inverse relationship between farm size and productivity. Both relations possess a similar turning point around 16,500 hectares. For policy analyses purposes, the actual relationship is the inverse as the turning points are far above the average farm-size in the region. Thus, the current trend of land concentration in BLA will lead to worse environmental and economic scenarios. More land will be wasted as the farms become larger. Furthermore, agriculture supply side responses to the growing future demand will come from conversion of natural vegetation into agricultural uses.

4. General Conclusions

This study aimed to assess two land use issues in Brazilian Legal Amazon. In chapter **2. Climate Change, Climate Risk and Land Use in Brazilian Legal Amazon**, we investigated farmers' land allocation decisions, highlighting the role of climate variables and risk-aversion. We used the results of this chapter to simulate climate change impacts on land use in Brazilian Legal Amazon. In chapter **3**. **Farm Size and Land Use Efficiency in Brazilian Amazon**, we studied the relationship between farm size and efficiency measures. Both chapters could be useful for policy analyzes.

Land use results show that climate variables are relevant determinants of land allocation. Furthermore, cattle production seems to be a hedging strategy as an increase in climate variability favors the establishments of pasture. Overall, simulation results point out that forest and cropland will give place to pasture in the future. An increase in climate variability will foster this process of land use change. We suggest application of land use planning and zoning to avoid this process of conversion of natural vegetation into pasture.

We found an inverse relationship between farm size and productivity. Thus, current process of land concentration in Brazilian Legal Amazon would lead to a lower agricultural production. Land will be wasted and agricultural production will decrease as smallholder farmers give space to large ones. We also found that the recurrent technical efficiency indicator is not a good measure of agricultural land waste. Land use efficiency results shows that the current agricultural output could be performed using less land. These findings indicate that the economic benefits from agricultural production are far below from its potential.

The main results in the two previous chapters predict a challenging future to policymakers. Climate change and the land concentration trend will worse environmental indicator in Brazilian Legal Amazon. Therefore, there is a need to establish policies to anticipate to these scenarios. Command and control policies should be applied to avoid deforestation, once climate change could make cattle production more attractive in some areas. Regarding land use efficiency, there is a need to understand the process of land concentration in order to provide policy alternatives.

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APPENDIX

Table A1. Number and area of establishments by size in Brazil and BLA (1985, 1995 and 2006)

Farm-size	1985							
	Brazil				Legal Amazon			
	Establishments		Area		Establishments		Area	
	Number	%	10^6 ha	%	Number	%	10^6 ha	%
Less than 10 ha	3,064,822	52.91	9.99	2.66	638,573	55.60	2.30	1.97
From 10 to less than 100 ha	2,160,340	37.29	69.57	18.55	351,278	30.58	13.55	11.59
From 100 to less than 1000 ha	517,431	8.93	131.43	35.06	142,370	12.40	31.38	26.86
More than 1000 ha	50,411	0.87	163.94	43.73	16,315	1.42	69.60	59.58
Farm-size	**1995**							
	Brazil				Legal Amazon			
	Establishments		Area		Establishments		Area	
	Number	%	10^6 ha	%	Number	%	10^6 ha	%
Less than 10 ha	2,402,374	49.65	7.88	2.23	416,704	47.56	1.76	1.44
From 10 to less than 100 ha	1,916,487	39.61	62.69	17.73	313,533	35.78	12.69	10.44
From 100 to less than 1000 ha	469,964	9.71	123.54	34.94	128,304	14.64	31.30	25.74
More than 1000 ha	49,358	1.02	159.49	45.10	17,714	2.02	75.85	62.38
Farm-size	**2006**							
	Brazil				Legal Amazon			
	Establishments		Area		Establishments		Area	
	Number	%	10^6 ha	%	Number	%	10^6 ha	%
Less than 10 ha	2,477,151	50.34	7.80	2.34	277,535	35.37	1.57	1.33
From 10 to less than 100 ha	1,971,600	40.07	62.89	18.85	358,921	45.74	14.54	12.29
From 100 to less than 1000 ha	424,288	8.62	112.84	33.82	129,265	16.47	32.64	27.61
More than 1000 ha	47,578	0.97	150.14	45.00	18,927	2.41	69.48	58.77

Source: IBGE (2014).

Table A2. Land use equations parameters estimations for 1946-2005 climate variables for BLA in 2006

	(1)		(2)		(3)	
	Cropland	Pasture	Cropland	Pasture	Cropland	Pasture
Crop price	2.340***	0.275	2.554**	0.373	2.390**	-0.134
	(0.861)	(1.515)	(1.009)	(1.542)	(0.999)	(1.591)
Cattle price	-1.534	2.351	-1.536	-0.538	-1.001	0.203
	(1.014)	(1.647)	(1.121)	(2.168)	(1.205)	(2.479)
Forest price	-1.621**	-0.912	-1.272*	-1.079	-1.368**	-1.287
	(0.711)	(0.948)	(0.665)	(1.052)	(0.680)	(1.193)
Land	0.0581***	0.446***	0.0580***	0.446***	0.0572***	0.447***
	(0.0114)	(0.0404)	(0.0114)	(0.0404)	(0.0115)	(0.0402)
Capital	0.0000240	0.0000304	0.0000244	0.0000313	0.0000250	0.0000311
	(0.000071)	(0.0000883)	(0.0000719)	(0.0000876)	(0.0000728)	(0.0000874)
Mean temperature	0.00484	-5.883	0.115	-4.102	0.430	-1.550
	(3.416)	(6.561)	(3.332)	(6.417)	(3.334)	(6.089)
Accumulated Rainfall	0.00508	-0.0253**	0.0115**	-0.0588***	0.00896*	-0.0546***
	(0.00359)	(0.0105)	(0.00558)	(0.0212)	(0.00517)	(0.0186)
Inter-annual temperature variance	0.144*	-0.0702	0.112	0.000765	0.105	0.00297
	(0.0751)	(0.125)	(0.0749)	(0.116)	(0.0728)	(0.116)
Inter-annual rainfall variance	-0.00000018	0.00000244**	-3.72e-08	0.00000137	-2.57e-08	0.00000124
	(0.0000005)	(0.00000122)	(0.000000578)	(0.00000102)	(0.000000522)	(0.00000102)
Inter-annual climate covariance	0.00126	0.000927	0.000900	0.00196	0.00101	0.00120
	(0.00137)	(0.00280)	(0.00153)	(0.00310)	(0.00141)	(0.00291)
Intra-annual temperature variance	6.420	23.45**	3.108	26.30**	1.660	26.14**
	(4.326)	(10.93)	(4.386)	(11.74)	(4.191)	(11.69)
Intra-annual rainfall variance	-0.0000418	0.000606	-0.000314	0.00167	-0.000290	0.00184
	(0.000482)	(0.00108)	(0.000557)	(0.00124)	(0.000556)	(0.00125)
Intra-annual climate covariance	-0.0991	-0.249	-0.0435	-0.228	-0.00381	-0.157
	(0.129)	(0.203)	(0.138)	(0.250)	(0.129)	(0.250)
Constant	-7.984	163.7	-635.1	3132.7	-143.9	4438.0
	(89.20)	(172.6)	(3309.1)	(17755.5)	(3477.4)	(17397.0)
Land tenure	yes		yes		yes	
Agronomic	no		yes		yes	
Institutions	no		no		yes	

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A3. Land use equations parameters estimations for 1966-2005 climate variables for BLA in 2006

	(1)		(2)		(3)	
	Cropland	Pasture	Cropland	Pasture	Cropland	Pasture
Crop price	2.478***	0.281	2.535**	0.344	2.350**	-0.117
	(0.879)	(1.532)	(0.997)	(1.544)	(0.989)	(1.622)
Cattle price	-1.481	3.082*	-1.362	0.442	-0.805	0.851
	(0.973)	(1.739)	(1.050)	(2.269)	(1.170)	(2.619)
Forest price	-1.735**	-1.053	-1.297*	-1.419	-1.390**	-1.507
	(0.741)	(0.965)	(0.683)	(1.046)	(0.693)	(1.175)
Land	0.0580***	0.446***	0.0578***	0.446***	0.0571***	0.446***
	(0.0114)	(0.0404)	(0.0114)	(0.0403)	(0.0115)	(0.0402)
Capital	0.0000239	0.0000307	0.0000243	0.0000317	0.0000249	0.0000316
	(0.0000713)	(0.0000874)	(0.0000719)	(0.0000871)	(0.0000728)	(0.0000868)
Mean temperature	0.228	-3.720	-0.144	-0.230	0.0829	1.943
	(3.558)	(6.741)	(3.768)	(6.605)	(3.728)	(6.369)
Accumulated Rainfall	0.00397	-0.0240**	0.0109**	-0.0502**	0.00850	-0.0463**
	(0.00366)	(0.0115)	(0.00546)	(0.0207)	(0.00527)	(0.0184)
Inter-annual temperature variance	0.161**	-0.0326	0.128**	0.0295	0.126**	0.00498
	(0.0628)	(0.0866)	(0.0603)	(0.0864)	(0.0578)	(0.0824)
Inter-annual rainfall variance	-0.000000219	0.00000309**	-0.000000102	0.00000201*	-8.83e-08	0.00000182*
	(0.000000489)	(0.00000128)	(0.000000534)	(0.00000108)	(0.000000477)	(0.00000108)
Inter-annual climate covariance	0.00191	-0.00126	0.00189	-0.000807	0.00201*	-0.00187
	(0.00118)	(0.00303)	(0.00117)	(0.00302)	(0.00110)	(0.00288)
Intra-annual temperature variance	6.086	23.35**	2.298	25.01**	0.782	26.22**
	(4.280)	(10.62)	(4.275)	(11.30)	(4.120)	(11.32)
Intra-annual rainfall variance	-0.0000672	0.000994	-0.000380	0.00202	-0.000369	0.00224*
	(0.000561)	(0.00113)	(0.000629)	(0.00126)	(0.000632)	(0.00128)
Intra-annual climate covariance	-0.102	-0.172	-0.0706	-0.0866	-0.0343	-0.0226
	(0.129)	(0.202)	(0.153)	(0.256)	(0.142)	(0.255)
Constant	-11.67	96.69	-576.4	3245.9	-101.1	4494.2
	(93.58)	(176.5)	(3284.0)	(17985.7)	(3553.3)	(17898.2)
Land tenure	yes		yes		yes	
Agronomic	no		yes		yes	
Institutions	no		no		yes	

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A4. Land use selection parameters estimations for 1946-2005 climate variables for BLA in 2006

	(1)			(2)			(3)		
	Cropland	Pasture	Forest	Cropland	Pasture	Forest	Cropland	Pasture	Forest
Crop price	-0.0311	0.0172	0.00750	-0.0288	-0.0364**	-0.0248	-0.0264	-0.0366**	-0.0245
	(0.0299)	(0.0148)	(0.0152)	(0.0332)	(0.0163)	(0.0166)	(0.0335)	(0.0163)	(0.0167)
Cattle price	0.0891**	-0.0689***	0.0235	0.0761*	-0.00713	0.0937***	0.0795*	-0.00466	0.101***
	(0.0394)	(0.0186)	(0.0195)	(0.0450)	(0.0217)	(0.0221)	(0.0453)	(0.0218)	(0.0223)
Forest price	0.0347	-0.0189	-0.0571***	0.0259	-0.00463	-0.0733***	0.0228	-0.00581	-0.0767***
	(0.0292)	(0.0122)	(0.0118)	(0.0310)	(0.0136)	(0.0129)	(0.0311)	(0.0137)	(0.0130)
Land	-0.000176***	0.000246*	0.000187	-0.000172***	0.000148	0.000183	-0.000176***	0.000150	0.000180
	(0.0000412)	(0.000128)	(0.000122)	(0.0000416)	(0.000130)	(0.000127)	(0.0000417)	(0.000131)	(0.000128)
Capital	0.00000966***	9.78e-09	0.00000620***	0.00000986***	2.42e-08	0.00000618***	0.00000979***	2.51e-08	0.00000600***
	(0.00000330)	(0.000000194)	(0.00000185)	(0.00000332)	(0.000000163)	(0.00000186)	(0.00000330)	(0.000000166)	(0.00000188)
Mean temperature	0.0862	0.00998	-0.0773**	0.0998*	-0.107**	-0.0728*	0.0991	-0.101**	-0.0677
	(0.0533)	(0.0403)	(0.0373)	(0.0601)	(0.0465)	(0.0427)	(0.0603)	(0.0467)	(0.0428)
Accumulated Rainfall	-0.000143	-0.000547***	0.000307***	-0.000200	-0.000886***	0.000408***	-0.000201	-0.000876***	0.000436***
	(0.000154)	(0.0000887)	(0.0000879)	(0.000213)	(0.000123)	(0.000118)	(0.000217)	(0.000123)	(0.000120)
Inter-annual temperature variance	-0.00172***	0.00418***	0.00230***	-0.00148**	0.00106	0.00135	-0.00142**	0.00106	0.00146*
	(0.000548)	(0.000949)	(0.000835)	(0.000588)	(0.000973)	(0.000894)	(0.000592)	(0.000971)	(0.000878)
Inter-annual rainfall variance	2.65e-08***	-9.85e-09**	-8.56e-09	2.04e-08**	-1.10e-08**	-3.27e-09	1.86e-08*	-1.10e-08**	-5.58e-09
	(1.02e-08)	(3.84e-09)	(5.57e-09)	(1.03e-08)	(4.41e-09)	(6.15e-09)	(1.04e-08)	(4.41e-09)	(5.50e-09)
Inter-annual climate covariance	-0.0000289	-0.0000514***	0.0000200	-0.0000189	0.00000352	0.00000511	-0.0000164	0.00000238	0.00000626
	(0.0000188)	(0.0000164)	(0.0000135)	(0.0000202)	(0.0000179)	(0.0000148)	(0.0000205)	(0.0000181)	(0.0000149)
Intra-annual temperature variance	-0.232***	-0.0393	-0.0359	-0.229**	-0.0576	-0.0423	-0.209**	-0.0573	-0.0231
	(0.0790)	(0.0647)	(0.0544)	(0.0913)	(0.0752)	(0.0596)	(0.0932)	(0.0766)	(0.0603)
Intra-annual rainfall variance	-0.00000241	0.0000121*	-0.0000181***	0.00000158	0.0000339***	-0.00000606	0.00000180	0.0000339***	-0.00000655
	(0.0000122)	(0.00000674)	(0.00000682)	(0.0000132)	(0.00000747)	(0.00000741)	(0.0000132)	(0.00000748)	(0.00000741)
Intra-annual climate covariance	0.00402**	0.00232**	-0.000636	0.00574***	-0.00539***	-0.00253*	0.00590***	-0.00514***	-0.00211
	(0.00164)	(0.00111)	(0.00106)	(0.00207)	(0.00151)	(0.00140)	(0.00212)	(0.00154)	(0.00142)
Constant	0.660	3.294***	4.078***	22.16	13.46*	39.70	12.56	13.45*	37.47
	(1.357)	(1.029)	(0.947)	(38.33)	(7.068)	(24.54)	(38.76)	(6.946)	(24.84)
Land tenure		yes			yes			yes	
Agronomic		no			yes			yes	
Institutions		no			no			yes	

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A5. Land use selection parameters estimations for 1966-2005 climate variables for BLA in 2006

	(1)			(2)			(3)		
	Cropland	Pasture	Forest	Cropland	Pasture	Forest	Cropland	Pasture	Forest
Crop price	-0.0362	0.0181	0.00789	-0.0315	-0.0383**	-0.0234	-0.0288	-0.0384**	-0.0233
	(0.0298)	(0.0148)	(0.0152)	(0.0332)	(0.0163)	(0.0166)	(0.0335)	(0.0163)	(0.0167)
Cattle price	0.0863**	-0.0755***	0.0206	0.0720	-0.00350	0.0919***	0.0757*	-0.00111	0.0992***
	(0.0390)	(0.0185)	(0.0195)	(0.0450)	(0.0217)	(0.0221)	(0.0453)	(0.0219)	(0.0223)
Forest price	0.0390	-0.0204*	-0.0565***	0.0293	-0.00594	-0.0737***	0.0259	-0.00707	-0.0772***
	(0.0294)	(0.0122)	(0.0118)	(0.0314)	(0.0136)	(0.0129)	(0.0314)	(0.0137)	(0.0130)
Land	-0.000177***	0.000250**	0.000190	-0.000173***	0.000145	0.000184	-0.000177***	0.000147	0.000181
	(0.0000411)	(0.000126)	(0.000120)	(0.0000415)	(0.000129)	(0.000126)	(0.0000416)	(0.000130)	(0.000127)
Capital	0.00000970***	-4.52e-10	0.00000596***	0.00000988***	1.76e-08	0.00000618***	0.00000985***	1.82e-08	0.00000601***
	(0.00000327)	(0.000000155)	(0.00000186)	(0.00000329)	(0.000000144)	(0.00000184)	(0.00000327)	(0.000000145)	(0.00000186)
Mean temperature	0.0815	0.0107	-0.0646*	0.0994*	-0.117**	-0.0614	0.100*	-0.112**	-0.0569
	(0.0531)	(0.0403)	(0.0371)	(0.0589)	(0.0458)	(0.0418)	(0.0591)	(0.0460)	(0.0419)
Accumulated Rainfall	-0.0000984	-0.000613***	0.000331***	-0.000177	-0.000918***	0.000433***	-0.000180	-0.000911***	0.000461***
	(0.000160)	(0.0000926)	(0.0000920)	(0.000215)	(0.000125)	(0.000120)	(0.000219)	(0.000125)	(0.000121)
Inter-annual temperature variance	-0.00206***	0.00187***	0.00216***	-0.00167***	0.000836	0.00114*	-0.00157***	0.000826	0.00123*
	(0.000501)	(0.000676)	(0.000625)	(0.000545)	(0.000654)	(0.000646)	(0.000555)	(0.000657)	(0.000641)
Inter-annual rainfall variance	2.55e-08**	-1.66e-08***	-7.54e-09	1.89e-08*	-1.31e-08***	-2.69e-09	1.73e-08	-1.32e-08***	-5.06e-09
	(1.03e-08)	(3.51e-09)	(5.65e-09)	(1.06e-08)	(4.05e-09)	(6.15e-09)	(1.09e-08)	(4.03e-09)	(5.68e-09)
Inter-annual climate covariance	-0.0000364*	-0.0000160	-0.00000603	-0.0000304	0.0000345**	-0.000000731	-0.0000272	0.0000336**	-0.000000694
	(0.0000193)	(0.0000155)	(0.0000143)	(0.0000202)	(0.0000166)	(0.0000147)	(0.0000206)	(0.0000168)	(0.0000148)
Intra-annual temperature variance	-0.211***	-0.0493	-0.0262	-0.205**	-0.0927	-0.0628	-0.188**	-0.0922	-0.0418
	(0.0782)	(0.0641)	(0.0557)	(0.0918)	(0.0755)	(0.0608)	(0.0938)	(0.0770)	(0.0617)
Intra-annual rainfall variance	-0.00000404	0.0000160**	-0.0000169**	0.00000161	0.0000341***	-0.00000712	0.00000219	0.0000341***	-0.00000764
	(0.0000132)	(0.00000733)	(0.00000737)	(0.0000141)	(0.00000806)	(0.00000795)	(0.0000142)	(0.00000808)	(0.00000797)
Intra-annual climate covariance	0.00381**	0.00259**	-0.000493	0.00583***	-0.00538***	-0.00187	0.00599***	-0.00516***	-0.00146
	(0.00159)	(0.00108)	(0.00104)	(0.00199)	(0.00148)	(0.00136)	(0.00203)	(0.00150)	(0.00138)
Constant	0.714	3.444***	3.673***	22.03	14.64**	40.06	12.61	14.56**	38.30
	(1.359)	(1.032)	(0.943)	(38.80)	(6.966)	(24.51)	(39.12)	(6.874)	(24.82)
Land tenure		yes			yes			yes	
Agronomic		no			yes			yes	
Institutions		no			no			yes	

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A6. Land use selection parameters estimations for 1986-2005 climate variables for BLA in 2006

	(1)			(2)			(3)		
	Cropland	Pasture	Forest	Cropland	Pasture	Forest	Cropland	Pasture	Forest
Crop price	-0.0367	0.0112	0.00809	-0.0358	-0.0410**	-0.0221	-0.0334	-0.0409**	-0.0221
	(0.0292)	(0.0147)	(0.0151)	(0.0325)	(0.0162)	(0.0166)	(0.0328)	(0.0162)	(0.0167)
Cattle price	0.0857**	-0.0772***	0.0161	0.0673	0.00160	0.0913***	0.0728	0.00290	0.0993***
	(0.0380)	(0.0187)	(0.0193)	(0.0438)	(0.0219)	(0.0220)	(0.0443)	(0.0220)	(0.0223)
Forest price	0.0324	-0.0160	-0.0553***	0.0268	-0.00292	-0.0732***	0.0235	-0.00366	-0.0767***
	(0.0289)	(0.0122)	(0.0118)	(0.0308)	(0.0136)	(0.0129)	(0.0309)	(0.0137)	(0.0130)
Land	-0.000171***	0.000233*	0.000184	-0.000170***	0.000136	0.000178	-0.000174***	0.000138	0.000177
	(0.0000408)	(0.000125)	(0.000120)	(0.0000413)	(0.000129)	(0.000129)	(0.0000415)	(0.000129)	(0.000130)
Capital	0.00000930***	3.87e-09	0.00000615***	0.00000966***	2.56e-08	0.00000630***	0.00000966***	2.65e-08	0.00000602***
	(0.00000324)	(0.000000141)	(0.00000185)	(0.00000328)	(0.000000150)	(0.00000185)	(0.00000327)	(0.000000153)	(0.00000187)
Mean temperature	0.0768	-0.0230	-0.0766**	0.0870	-0.120***	-0.0651	0.0878	-0.117**	-0.0642
	(0.0536)	(0.0412)	(0.0376)	(0.0585)	(0.0464)	(0.0419)	(0.0586)	(0.0465)	(0.0419)
Accumulated Rainfall	-0.000148	-0.000466***	0.000357***	-0.000242	-0.000715***	0.000473***	-0.000239	-0.000709***	0.000502***
	(0.000158)	(0.0000882)	(0.0000885)	(0.000208)	(0.000120)	(0.000117)	(0.000211)	(0.000120)	(0.000117)
Inter-annual temperature variance	-0.00166***	0.00186**	0.00237***	-0.00123**	0.000320	0.00124*	-0.00120**	0.000299	0.00134*
	(0.000533)	(0.000800)	(0.000739)	(0.000579)	(0.000761)	(0.000736)	(0.000582)	(0.000765)	(0.000742)
Inter-annual rainfall variance	2.47e-08*	-4.33e-08***	-1.61e-08*	1.60e-08	-1.77e-08**	-7.36e-09	1.55e-08	-1.76e-08*	-8.71e-09
	(1.31e-08)	(7.57e-09)	(8.48e-09)	(1.37e-08)	(9.03e-09)	(9.08e-09)	(1.37e-08)	(9.03e-09)	(8.97e-09)
Inter-annual climate covariance	-0.0000246	0.0000439***	0.0000104	-0.0000209	0.0000310*	0.0000133	-0.0000213	0.0000297*	0.0000119
	(0.0000160)	(0.0000161)	(0.0000142)	(0.0000167)	(0.0000161)	(0.0000146)	(0.0000168)	(0.0000161)	(0.0000147)
Intra-annual temperature variance	-0.258***	0.0732	-0.00581	-0.239***	0.0184	-0.0800	-0.214**	0.0208	-0.0595
	(0.0749)	(0.0648)	(0.0526)	(0.0880)	(0.0764)	(0.0576)	(0.0897)	(0.0777)	(0.0583)
Intra-annual rainfall variance	-0.00000739	0.0000138*	-0.0000210***	-0.00000200	0.0000311***	-0.0000117	-0.00000174	0.0000311***	-0.0000127
	(0.0000134)	(0.00000760)	(0.00000762)	(0.0000146)	(0.00000847)	(0.00000835)	(0.0000148)	(0.00000849)	(0.00000837)
Intra-annual climate covariance	0.00366**	0.000772	-0.00113	0.00537***	-0.00639***	-0.00214*	0.00553***	-0.00628***	-0.00181
	(0.00149)	(0.00102)	(0.000964)	(0.00179)	(0.00136)	(0.00123)	(0.00182)	(0.00138)	(0.00124)
Constant	1.105	4.012***	4.014***	20.92	14.53*	42.04*	11.32	14.46*	41.00*
	(1.376)	(1.067)	(0.967)	(39.09)	(7.571)	(24.65)	(39.38)	(7.467)	(24.90)
Land tenure		yes			yes			yes	
Agronomic		no			yes			yes	
Institutions		no			no			yes	

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A7. Selection estimations for 1986-2005 climate variables without irrigated municipalities or representative farms with few respondents

	(1)			(2)			(3)		
	Cropland	Pasture	Forest	Cropland	Pasture	Forest	Cropland	Pasture	Forest
Crop price	-0.0363	-0.0351**	-0.0183	-0.0368	-0.0371**	-0.0387**	-0.0292	-0.0448**	-0.0412*
	(0.0328)	(0.0164)	(0.0169)	(0.0397)	(0.0186)	(0.0193)	(0.0761)	(0.0225)	(0.0244)
Cattle price	0.0764*	-0.00643	0.0954***	0.0758	-0.00547	0.111***	0.0672	-0.0113	0.104***
	(0.0444)	(0.0223)	(0.0225)	(0.0588)	(0.0253)	(0.0258)	(0.0975)	(0.0308)	(0.0325)
Forest price	0.0250	-0.00346	-0.0785***	0.0104	-0.00881	-0.0800***	0.00272	0.00447	-0.0764***
	(0.0310)	(0.0137)	(0.0131)	(0.0366)	(0.0157)	(0.0151)	(0.0546)	(0.0189)	(0.0183)
Land	-0.000167***	0.000320**	0.000399***	-0.000301***	0.00163***	0.00376***	-0.000784***	0.00184**	0.00997***
	(0.0000414)	(0.000149)	(0.0000998)	(0.0000833)	(0.000547)	(0.000958)	(0.000238)	(0.000779)	(0.00211)
Capital	0.00000913***	-2.45e-08	0.00000531***	0.0000195**	-0.000000134	0.00000755	0.0000753***	0.0000265	0.0000109
	(0.00000322)	(0.000000123)	(0.00000176)	(0.00000818)	(0.000000327)	(0.00000916)	(0.0000282)	(0.0000172)	(0.0000177)
Mean temperature	0.0717	-0.0974**	-0.0410	0.0365	-0.126**	-0.00950	0.00274	-0.168**	-0.0310
	(0.0594)	(0.0474)	(0.0427)	(0.0800)	(0.0594)	(0.0493)	(0.127)	(0.0784)	(0.0625)
Accumulated Rainfall	-0.000226	-0.000764***	0.000464***	0.000279	-0.000971***	0.000446***	-0.0000949	-0.000886***	0.000458**
	(0.000213)	(0.000123)	(0.000121)	(0.000294)	(0.000147)	(0.000140)	(0.000453)	(0.000189)	(0.000178)
Inter-annual temperature variance	-0.00118**	0.000352	0.00132*	-0.00135*	0.000205	0.00140	-0.00174	0.0000269	0.000783
	(0.000583)	(0.000779)	(0.000743)	(0.000776)	(0.000895)	(0.000871)	(0.00114)	(0.00110)	(0.000963)
Inter-annual rainfall variance	1.36e-08	-2.08e-08**	-1.10e-08	5.15e-09	-2.09e-08*	-1.36e-08	5.34e-09	-3.08e-08**	-1.23e-08
	(1.38e-08)	(1.01e-08)	(9.79e-09)	(1.72e-08)	(1.12e-08)	(1.11e-08)	(2.76e-08)	(1.42e-08)	(1.39e-08)
Inter-annual climate covariance	-0.0000222	0.0000306*	0.0000111	-0.00000971	0.0000372*	0.0000158	-0.0000120	0.0000621**	0.0000156
	(0.0000168)	(0.0000167)	(0.0000151)	(0.0000218)	(0.0000213)	(0.0000180)	(0.0000319)	(0.0000309)	(0.0000223)
Intra-annual temperature variance	-0.224**	0.0216	-0.0514	-0.227*	-0.0278	-0.121*	-0.176	0.0930	-0.203**
	(0.0914)	(0.0801)	(0.0598)	(0.128)	(0.108)	(0.0687)	(0.185)	(0.142)	(0.0832)
Intra-annual rainfall variance	-0.00000522	0.0000379***	-0.00000602	-0.0000443**	0.0000331***	-0.00000771	-0.0000332	0.0000270**	-0.0000144
	(0.0000152)	(0.00000887)	(0.00000874)	(0.0000198)	(0.0000101)	(0.0000100)	(0.0000309)	(0.0000126)	(0.0000125)
Intra-annual climate covariance	0.00519***	-0.00595***	-0.00117	0.00444*	-0.00651***	-0.000493	0.00824**	-0.0107***	0.00125
	(0.00184)	(0.00142)	(0.00128)	(0.00251)	(0.00174)	(0.00147)	(0.00391)	(0.00243)	(0.00187)
Constant	13.51	13.63*	41.95*	-28.18	19.28***	46.14*	-45.71	21.10**	48.89
	(39.36)	(7.575)	(25.10)	(42.99)	(7.351)	(26.94)	(71.15)	(9.187)	(37.56)
Observations	6840			6381			5447		

(1) Without municipalities with irrigation, (2) without representative farms with less than 15 respondents, and (3) without representative farms with less than 30 respondents. Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A8. Estimation of technical efficiency with full translog production function for BLA in 2006

	(1)	(2)	(3)	(4)
Frontier				
Land	0.270***	0.268***	0.279***	0.274***
	(0.0849)	(0.0755)	(0.0856)	(0.0830)
Labor	0.482	0.503	0.273	0.277
	(0.651)	(0.667)	(0.673)	(0.663)
Capital	-0.367***	-0.351***	-0.420***	-0.404***
	(0.116)	(0.111)	(0.129)	(0.125)
Land^2	-0.00365	-0.00402	-0.00137	-0.00172
	(0.00942)	(0.00915)	(0.00945)	(0.00934)
Labor^2	0.226	0.240	0.188	0.200
	(0.214)	(0.212)	(0.221)	(0.211)
Capital^2	0.0812***	0.0773***	0.0880***	0.0841***
	(0.0163)	(0.0152)	(0.0180)	(0.0173)
Land*Labor	-0.177**	-0.184**	-0.194**	-0.201**
	(0.0837)	(0.0819)	(0.0849)	(0.0832)
Land*Capital	-0.0206*	-0.0188*	-0.0221**	-0.0200*
	(0.0110)	(0.00983)	(0.0111)	(0.0109)
Labor*Capital	0.105	0.104	0.135	0.135
	(0.0818)	(0.0824)	(0.0856)	(0.0836)
Constant	7.629***	7.556***	8.183***	8.108***
	(0.434)	(0.428)	(0.515)	(0.496)
AIC	16465.0	16384.3	16457.5	16373.3
BIC	16544.5	16516.8	16537.0	16505.7
TE distribution	Half-normal	Half-normal	Exponential	Exponential
State FE	no	yes	no	yes
Lambda	0.00592	0.00758	0.371***	0.390***

Standard errors in parentheses: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A9. Elasticities of production, returns to scale, technical and land use efficiencies for the full translog specification for BLA in 2006[33]

	mean	sd	min	max
Land	0.101	0.069	-1.026	0.292
Labor	1.004	0.288	-0.505	2.802
Capital	0.247	0.131	-0.469	1.397
Returns to scale	1.352	0.323	-0.525	3.263
TE	0.732	0.054	0.040	0.900
LUE	0.079	0.069	0.000	0.489

[33] We weighted summary statistics by the number of respondents. We utilized all coefficients in Table A8 to construct the indicators.