ROADS, DEFORESTATION, AND GHG EMISSIONS: THE ROLE OF FOREST GOVERNANCE AND CARBON TAX POLICY IN PARÁ AND MATO GROSSO, BRAZIL

by

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To my wife Maria Clara, to Ana Sofia my daughter, and to Martin, my son. Thanks for every smile and your unconditional support. To my parents Jose Luis and Gloria, thanks for guiding me on this journey. To Lucho, Ana Maria, and Juan Jose, I love you!

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ABSTRACT

This research explores the impact of road infrastructure on deforestation, the role of forest governance and a carbon tax/credit mechanism in mitigating the effect on land use change and subsequent GHG emissions, with application to the states of Pará and Mato Grosso in Brazil. Few studies have addressed how policies to protect forested land affect the rate of deforestation associated with road and infrastructure improvement. This research makes three main contributions to the literature of roads and deforestation: 1) the concept of cost of access to the "closest" market in terms of time (expressed in person hours per ten ton load) is introduced to reflect variations in the road network infrastructure; 2) development of empirical evidence of the role of forest governance in diminishing the rate of deforestation linked to roads, using data from Brazil; and 3) and assessment of the efficacy of a carbon tax/credit scheme for mitigating the impact of infrastructure investment on land use and resultant changes in GHG emissions. Access cost ranged between 0.01 and 3084 person hours per load, however 80 percent of the pixels measured less than 784 person hours across the three years analyzed (2003, 2013, and 2018). This measure facilitated a contrast in spatial accessibility due to road infrastructure across pixels within the same year and across years on a same pixel. The use of a fractional logit model allowed the incorporation of proportions of different land uses within a same pixel at the same resolution of other variables not available at the same fine scale. Strong forest governance reduced up to 25% the elasticities on forest lands with respect to access cost; in other words, the impact of roads on deforestation is reduced by one fourth when forest governance is strengthened. These larger impacts occur at the frontier where most of the efforts need to be addressed. Finally, provided a shock in road infrastructure, a carbon tax/credit level of $82/tCO2e permitted to abate an additional amount of GHG emissions estimated in 244 million tons of CO2e released due to changes in carbon stocks and flow emissions from agricultural activities induced from changes in road infrastructure. More importantly, this research provided insights of a proportion of GHG emissions that could be abated at different levels of a carbon tax/credit.

CHAPTER 1. INTRODUCTION

The Brazilian Amazon has lost forest on more than 718 thousand hectares since 1970 (Butler, 2020). Different authors agree that one of the main drivers has been the development and improvement of roads (Barber et al., 2014; Belloumi, 2009; Chomitz and Thomas, 2001a; Iimi et al., 2015; Pfaff et al., 2018, 2007; Pfaff, 1999; Rosa et al., 2013a). The logic is straightforward in that improved accessibility reduces farm gate input costs and raises farm gate commodity prices as well as the profitability of timber harvesting. These changes create economic incentives to convert forest land to other uses and thus lead to deforestation, and consequently the release of Green House Gas (GHG) emissions.

At the 2015 United Nations Climate Change Conference (COP21), members of the United Nations signed the United Nations Framework Convention on Climate Change (UNFCCC). This agreement, well known as the Paris agreement, was meant to address efforts for keeping the increase of global temperature below 2 Celsius degrees (compared to pre-industrial levels). Under this agreement, every one of the 195 countries that signed, committed to a Nationally Determined Contribution (NDC) for reducing Green House Gas emissions. By 2018, 185 parties had ratified the agreement (“Paris Agreement - Status of Ratification | UNFCCC,” n.d.), including Brazil, whose NDC targeted a reduction of greenhouse emissions of 43% by 2030.

To achieve this goal, Brazil´s strategy includes raising the share of renewable sources, increasing the energy efficiency in the electricity sector, achieving zero illegal deforestation by 2030, restoring degraded pasturelands, and reforestation (Kossoy, n.d.). In the last decade, Brazil has demonstrated a strong commitment to the accomplishment of its environmental goals. By 2017, Brazil reduced the emissions of deforestation by 610 million tons of carbon dioxide (CO2), surpassing the targeted goal of 565 million of tons that was committed to for 2020 in the 2009 Copenhagen Accord to combat climate change (“Brazil cuts deforestation emissions below 2020 targets | Reuters,” n.d.).

“Brazil has committed through its National Climate Change Policy to further reducing deforestation in the Amazon to around 0.4M ha in 2020, and pledged through its Nationally

Determined Contribution (NDC) submitted to the UNFCCC to achieve zero illegal deforestation in the Amazon by 2030" (Tacconi et al., 2019).

Environmental regulation and enforcement of forest conservation helped Brazil attain these results. However, government data suggests that agricultural development contributes to deforestation. For instance, 17,500 km^2 out of 220,000 km^2 of forest lands that were cleared between 2006 and 2017 are now being used for soybean production ("New data on Trase shows soy trade from Brazil's Cerrado driving climate emissions | by Trase | trase | Medium," n.d.).

As part of the conservation policy efforts, the Federal Government of Brazil launched in 2004 the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAM). The PPCDAM is relevant to the enforcement of environmental protection laws, and facilitated integration and coordination of actions across government institutions for forest protection, such as permanent monitoring, environmental enforcement, and land tenure regularization (Diniz et al., 2015). For instance, deforestation rates (in thousand square kilometers) dropped from 27.8 to 19.01 in one single year, and that trend continued decreasing to 4.6 in 2012.

Few studies have addressed how policies to protect forested land affect the rate of deforestation associated with road and infrastructure improvement. Most of these studies based their analysis on a municipality level, and include into their assessment a variable that represents the density of roads into the unit of analysis. This research expands the literature of the impact of roads on deforestation, by applying a fractional logit model approach that integrates global databases of land soil characteristics for agriculture at a 5 arc-minute resolution with high resolution data on land cover changes and land protection status. It also incorporates the concept of "access cost" – a measure of transportation effort required to access the closest market – that is defined at the pixel level. In addition, it presents empirical evidence on how the effect of roads on deforestation might vary when protection policies are enforced, and evaluates the role of a tax/credit mechanism to mitigate the effect of roads on GHG emissions. While the primary focus is deforestation and associated emissions, the alternative land uses also have different emissions profiles and so some attention is given to estimating those other uses as well.

Even when Brazil does a good job in the reduction of emissions from deforestation, policy instruments are needed for regulating land-use change and the creating incentives that induce farmers and land holders to contribute to the country's environmental goals. The interest in these mechanisms is rising, and the Brazilian government is in the exploratory phase of carbon pricing policy assessment (World Bank, 2018). Furthermore, in 2019 the United Nation's Green Climate Fund approved a payment of $96 million to Brazil for the first proposal on REDD+ (efforts to reduce emissions from deforestation and forest degradation), that accounted for a reduction of 19 million tons of GHG emissions in 2014 and 2015, compared to the rates in the period 1996-2010 (Sax, 2019).

1.1 Scope and area of study

This study evaluates the relationship between road infrastructure and land cover applied to Pará and Mato Grosso, in Brazil. Studying this region is relevant because one third of the remaining rainforests in the world are located in Brazil, which includes two thirds of the Amazon rainforest. Pará and Mato Grosso are the two states with the largest accumulated deforestation in Brazil. Between 1988 and 2019 these two states were responsible for 67% of total deforestation in the Amazon. In these states, there have been major changes in federal roads, such as BR163 and BR230 and BR364. Improvement of the road infrastructure has increased the paved federal road network from 4,663 to 6,742 kilometers between 2000 and 2018 in these two states. Given that road infrastructure is crucial to boosting socioeconomic conditions in remote areas, it is expected that the road infrastructure will keep expanding and improving. Nonetheless, this research disentangles the side effects of roads on deforestation when forest protection policies are implemented, which is relatively unexplored.

Brazil has developed fine scale data on land cover change at the pixel level (with a resolution of a 30m x 30m) and geo-referenced road network data, and this data has been released for years 2011 and later. The implementation of the PPCDAM program, including a real time monitoring system on deforestation, protection of lands at national and departmental level, the actions taken by the private sector such as the moratorium of the Soy and Beef sector, among others, make of Brazil an interesting case for the assessment on changes in forest governance. In addition, a carbon tax/credit mechanism is implemented to offset potential emissions generated from changes in road infrastructure.

1.2 Objectives

This study focuses on understanding the relationship between road infrastructure and land cover, under different regimes of forest governance, and potential mitigation alternatives to reduce the effect of the former on GHG emissions. Three objectives are defined for this purpose:

1 Estimate the access cost to the closest market at the 5-arc minute pixel level for Pará and Mato Grosso, Brazil

2 Determine the effect of road infrastructure changes on land use transitions and the role of forest governance for Pará and Mato Grosso, Brazil

3 Estimate the size of a carbon tax/credit required to mitigate GHG emissions derived from road infrastructure changes at the regional level

1.3 Data

This research combines data from different sources and from different pixel resolutions on land cover, agricultural suitability, road infrastructure, land protection status, carbon stocks and GHG emissions. These sources are the Brazilian Annual Land Use and Land Cover Mapping Project (MAPBIOMAS), the Global Agroecological Zones (GAEZ) from FAO and IIASA, and the Brazilian agency for infrastructure DNIT (Brazilian National Department of Infrastructure), the Amazon Geo-referenced Socio-Environmental information network (RAISG). The data sample includes observations from 25,421 geographical locations at a pixel resolution of 5 arc-minutes of longitude and latitude, which is the highest pixel resolution available for the soil characteristics covariates. Additional information on land cover and soil characteristics is provided as follows:

Roads: The official federal road network for Brazil is used for this task. These roads were classified into planned roads, unpaved roads, paved roads, and double line roads.

Land cover: Geo-referenced layers for land cover from the MAPBIOMAS project were used. Five land types are considered for this study: forest, pastures, Crops, silviculture, and other land cover types. The MAPBIOMAS project is a multi-institutional effort to map Brazilian land cover and monitor changes. This project was created in 2015 by the Greenhouse Gas Emissions Estimation System (SEEG) from the Brazilian Climate Observatory (OC), with the support of a network that involved Universities, NGOs, and technology companies ("Mapbiomas Brasil," n.d.). Data from two periods are used for evaluating the two types of forest governance: 2003 (weak forest governance) and 2013 (strong governance). The former period represents the five year period of the highest deforestation rates before the year that PPCDAM was implemented, while the latter denotes the period that concluded the decreasing trend in deforestation rates that followed the program. For each forest governance regime, land cover is observed at the end of the corresponding period and a 5-year lag is used to reflect the inertia from previous land cover.

Soil characteristics: Data on soil characteristics are used as control variables as they represent conditions that could constrain land use for agriculture. Variables on nutrient availability (NUTC), nutrient retention capacity (NTRNTC), rooting conditions (ROOTC), oxygen availability to roots (OXGNC), and workability (WORK) were acquired from the GAEZ portal. All these variables are reported in that portal as category variables. Each of those variables can take a value between one to seven, representing diverse attributes that influence agricultural production; the larger the value the more restrictive conditions for agriculture. The variables considered here were transformed into dummy variables indicating whether or not a pixel holds severe constrains. Definition of those variables are extracted from the FAO-IIASA GAEZ model documentation, (Fischer et al., 2012):

"Nutrient availability is primarily determined by soil texture and pH. On one hand, soils with a large amount of clay or organic matter retain larger amounts of water and nutrients relative to sandy soils. On the other hand, the pH affects the chemical form of the nutrients that can be absorbed by the roots. (Most plants grow best on pH ranges between 5.5 and 7.5.)
"Nutrient retention capacity refers to the capacity of the soil to retain added nutrients against losses caused by leaching. This variable is affected by soil texture. Nutrient retention capacity is of particular importance for the effectiveness of fertilizer applications and is therefore of special relevance for intermediate and high input level Cropping conditions.

Rooting conditions may be affected by the presence of a soil phase either limiting the effective rooting depth or decreasing the effective volume accessible for root penetration.

Oxygen availability is largely defined by drainage characteristics of soils. Apart from drainage characteristics, the soil quality of oxygen availability may be influenced by soil and terrain characteristics that are defined through the occurrence of specific soil phases.

Workability, or ease of tillage, depends on interrelated soil characteristics such as texture, structure, organic matter content, soil consistency/bulk density, the occurrence of gravel or stones in the profile or at the soil surface, and the presence of continuous hard rock at shallow depth as well as rock outcrops".

This thesis is comprised by six chapters. Chapter 1 correspond to the introduction you are reading and Chapter 2 will present a literature review on the role of roads on deforestation, forest governance, and carbon pricing.

Because this research intends to describe the effect of road infrastructure on deforestation and the role of forest governance and carbon tax/credit policy, Chapter 3 will disclose geo-referenced road data into a spatial measure of access cost from every pixel of Pará and Mato Grosso to the nearest market in terms of travel time. The main question to be addressed in that chapter is what is the access cost to the markets? This exercise will be carried out for three years: 2003, 2013, and 2018; 2003 and 2013 will be used as representative years of two different periods of forest governance in Chapter 4, while 2018 will be used to implement a shock on access cost to evaluate the role of a carbon tax/credit policy to abate GHG emissions.

Chapter 4 will implement a land use model and assess the effect of access cost derived from road infrastructure on deforestation, and the role of forest governance; the two questions that will be addressed that chapter are: (1) what is the impact of access cost on land use? and (2) does forest governance affect the impact of access cost on deforestation?

Chapter 5 will assess the role of a carbon tax/credit as a mechanism to abate potential changes in land use derived from road infrastructure improvement. That chapter will use the model developed in the previous chapter to estimate a baseline scenario on land use and subsequent GHG emissions (using data of 2013) and will implement a shock on road infrastructure in which access cost is improved to the levels of 2018 (all else constant). Differences on net carbon (stock and flow) emissions are estimated and then a carbon tax/credit instrument is implemented to induce land users to reduce emissions. The question to be addressed in that chapter is what level of a carbon tax/credit could mitigate the effect of road improvement on GHG emissions? This thesis will conclude in Chapter 6, in which some concluding remarks will be presented.

CHAPTER 2. LITERATURE REVIEW

This chapter present a literature review that motivates this research. The review starts by describing some advances in the development of the road network in Brazil and offers a context on the role of road infrastructure as a driver of deforestation. Then, the mechanism for which the land transition from forest to other uses occurs is explained. Later, forest governance in Brazil is described, as well as the commitment of Brazil to the Paris agreement. Finally, the literature review ends by describing the relevance of carbon pricing mechanisms for avoid an increase of global average temperature below 2°C.

2.1 Road infrastructure and deforestation

Starting in 1970, the Brazilian Government established goals for building new infrastructure across Brazil (Program of National Integration-1970), that have generated new settlements and favored economic activity (Sanchez-Robles, 1998), but also have incentivized conversion of natural habitats to other uses (Laurance et al., 2001a). In the last 20 years, other initiatives have prioritized infrastructure development to promote economic growth, such as the Forward Brazil Program - also referred as Advance Brazil- (2000), Growth Acceleration Program (PAC:2007) which was extended until 2014. Amann et al. (2014) found that between 1990 and 2012, an increase of 1% in infrastructure investment has led to a 0.11% rise in Brazilian Regional GDP. Improvement of the road network that connects Mato Grosso and Pará states with the rest of Brazil has accelerated in the last 20 years, along with land conversion for agricultural purposes. Laurance et al. (2001a) assessed the effect of the implementation of the Forward Program on forest degradation, and estimated that unfragmented forest in Brazil would decline by 36% as a result of new highway construction by 2020; when contrasting deforestation rates between the scenarios with and without new infrastructure, those of the improved infrastructure were reported higher by 500,000 ha/year. This prediction revealed a substantial effect that roads may have on deforestation based on a business as usual scenario. However, after Lawrence's study was published, deforestation rates reverted to a downward trend that started in 2005. The drop-in deforestation rates are the result of efforts from different stakeholders to implement mechanisms to stop deforestation attributed to enhanced forest governance (See Chapter 1 and Chapter 4). Thus, a relevant question that arises and will be addressed in Chapter 4 is “what is the role of enhanced forest governance in diminishing the negative effects of roads on deforestation?”

Nonetheless, diverse studies have linked road connectivity improvements as one of the main drivers of deforestation. In the Amazon basin, about 84 percent (Chomitz and Thomas, 2001b) to 95 percent (Rosa et al., 2013b) of total deforestation occurs within 50 km of roads. Paved roads provide year-round access to forest resources, which otherwise would have no access in the rainy season, and reduce transportation costs impacting farmgate prices of inputs and outputs, and thus land returns (Laurance et al., 2009).

Highways appear to have an equal or larger effect on deforestation than local official roads. Highways connect municipalities with each other, while local roads improve connectivity within the same municipality. Laurance et al. (2001a) found for Brazil that highways and roads cause a similar deforestation pattern of about 30% of total area deforested within 10 km, but for areas located between 25 and 50 km from roads or highways, the deforested areas account for 15% in the case of highways but less than 15% for the case of roads. de Espindola et al. (2021) pointed out when assessing cropland expansion as a driver of deforestation for the Cerrado and Caatinga, that distance to the road does not play a protagonist role in deforestation patterns.

Asher et al. (2020) implemented two specifications to identify the effect of roads on forest loss: a two-stage least square specification to implement a local linear discontinuity regression, and a difference in differences. They evaluated the effect of the construction of new rural roads and the upgrading of highways on forest loss in India and found that new rural roads had zero effects on local deforestation, but the improvement of highways caused substantial forest loss. Ortega-Pacheco et al. (2019) developed an econometric model to estimate the economic determinants of forest land conversion in Esmeraldas, Ecuador and assessed the effect of transaction cost on climate change mitigation activities that rely on incentives. A logistic share model specification has been used to identify drivers of deforestation (Ortega-Pacheco et al., 2019). They evaluated the forest extraction rents, soil agricultural potential, population density, immigration rate, and land tenure, using municipalities as the unit of analysis.

Drivers of deforestation and household decisions change over time as the agricultural frontier evolves. On the one hand, a shorter distance to an urban center improves farm-gate prices of output, and the demand for agricultural land increases, negatively affecting deforestation; on the other hand, households with closer proximity to urban centers may have access to better employment opportunities that offer higher returns than agricultural activities or deforestation. Additionally, urbanization and manufacturing eventually consume farmland nearby to commercial centers. Wu & Sills (2018) state that household decisions and deforestation drivers change over time as the frontier evolves in the context of Ouro Preto do Oeste in Brazil. On the one hand, closer distances to urban centers improve farm-gate prices of output, and the demand for agricultural land increases which negatively affects deforestation; by the other hand, by getting closer to urban centers households may have access to better employment opportunities that offer higher returns than agricultural activities or deforestation. Besides, environmental regulation is more enforceable in the proximity of urban centers.

The impacts of road development on deforestation also depend on the prior level of development and prior deforestation (Pfaff et al., 2018). Road improvement in regions with intermediate prior development (e.g. pre-established municipalities) is expected to generate more deforestation than in regions already established where prior deforestation already occurred. Also in the short run, little deforestation is expected in undeveloped and isolated areas that are distant from urban centers; however, when environmental regulation is more stringently enforced, less deforestation is expected in the proximity to Urban centers as authorities could verify violations and react faster than in remote areas (Wu and Sills, 2018).

In the context of land-use change, the most common theoretical framework relies on the biophysical characteristics, economic characteristics at a given location and their effect on the probability of deforestation (Briassoulis, 2020), and also in the von Thünen theory where land use is driven by the effect of transportation cost and land tenure cost on profitability (Wu and Sills, 2018). Bio-physical drivers comprise characteristics such as weather, soil types, availability of natural resources, among others; while socio-economic drivers include social, economic, political, and institutional factors. Population density is often included as a socio-economic driver. However, Pfaff (1999), found that population density didn't have a significant effect on deforestation when other determinants were included; he argued that any eventual effect of population on deforestation would be greater from the first immigrants than of any increase of the population base. Following the same line, (Lambin et al., 2001) found that population and poverty are not the main drivers of land cover change; instead, people respond to market-driven economic opportunities, and those opportunities are affected by government policies and are attenuated by local factors.

2.2 The von Thünen framework

The von Thünen model on agricultural land location traces back to 1826 when Johann Heinrich von Thünen published his seminal work called "the Isolated State" (Krzymowski and Minneman, 1928; O'Kelly and Bryan, 1996; Sinclair, 1967), in which he addresses the circumstances for agriculture to be carried out intensively or extensively. Extensive systems refer to those enterprises that use little capital or labor per unit of area, and then a larger intensity means that capital and input are increasing gradually (Krzymowski and Minneman, 1928). Productivity per hectare for a given crop can be enhanced by more intense use of resources and inputs such as adequate soil preparation and fertilization, as well as the selection of high yield varieties. The cost of production increases relative to the level of intensity but so does the yield. This theory relies on the law of diminishing productivity, each additional unit of input decreases marginal productivity (Krzymowski and Minneman, 1928).

Under similar conditions, high prices of agricultural products make intensive farming more profitable, while low prices for agricultural commodities make those extensive activities to be more attractive. Consequently, intensive systems locate in those densely populated areas and extensive in those sparsely populated areas. The von Thünen approach is useful for explaining agricultural patterns driven by transportation costs to the markets. In that context, the patterns of intensive agriculture decrease as the distance from the urban centers arises (Sinclair, 1967). This framework fits well for underdeveloped economies, but for developed economies the pattern could be the opposite. In the latter, economic activity may not rely from agriculture and so agricultural lands may not be located close to the urban centers.

The von Thünen model, intended to understand the laws that drive the interaction of agricultural prices, land uses, and distance in a context of profit maximization (O'Kelly and Bryan, 1996). Von

Thünen developed the concept of land rents and the role of transportation costs in reducing those rents (Walker, 2021). Agricultural producers face decisions regarding what crop to product and where to sell the output. Because producers target the market centers where to send their products, by holding other factors[1] constant the influence of transport cost determines the location of crops and livestock production (O'Kelly and Bryan, 1996). The location of different systems is determined by the price at the farm of the agricultural outputs. Thus, provided some quantity and quality, the price the farmer will receive in the city is the same regardless of its origin, but the farm gate value will get reduced as the transportation cost increases (Krzymowski and Minneman, 1928). (Chomitz and Gray, 1996) implemented a land-use model under the von Thünen Framework: different potential rents can be extracted from a plot based on a set of the potential use of the plot, and land use will be chosen based on the agricultural activity that provides the highest rent. The model also assumes the land use is reversible, which could be possible under the implementation of incentives to mitigate GHG emissions. (Chomitz and Gray, 1996) evaluated the distance to market and the distance to the nearest roads as proxies of access cost. Nelson & Hellerstein (1997) proposed a model to assess the determinants of land use applied to Central Mexico under a von Thünen framework, similar to (Chomitz and Gray, 1996). Every parcel has a set of potential returns from a diversity of potential uses that might be profitable or not at a given time. The land-use choice is made by maximizing the net present value across all potential uses. Land use data is collected from satellite images, and geophysical variables and socioeconomic variables are used to identify changes in land use. Their results indicate that as the cost to access roads for a given cell increases, the probability of cropping that cell decreases, the chances for that location to remain in forest are much higher. Pfaff (1999) using county-level data for the period 1978-1988, found empirical evidence that land characteristics and factors that affect transport cost such as distance to the market are determinants of deforestation in the Brazilian Amazon. (Chomitz and Gray, 1999) proposed to include market distance in a land-use model, instead of using variables such as distance to the nearest road, and on-road travel to the market. In their study, they estimated the cost of transportation by integrating a distance measure with impedance values to different types of terrains. The research approach implemented in this thesis builds on (Chomitz and Gray, 1999) and implements a cost per load and a fractional land-use model.

[1] Other factors that incluence the decision of what to crop may include input and output prices, regulation, soil and climate aptitude for crops, etc.

Based on the arguments above, it is noteworthy to mention that the mechanism for land conversion from forest to pastures, crops, and other uses, is motivated in a von Thünen framework, where land use relies on how transportation and land tenure cost[2] affect the profitability of current use (Wu and Sills, 2018). The higher the cost of access to markets for inputs and outputs, the lower the probability of land conversion to crops and the higher the probability that a forest location will remain forested (Nelson and Hellerstein, 1997). Most applications of von Thünen use distance as a proxy of transportation cost; the approach undertaken in this thesis is more sophisticated because it takes into account different types of roads and as in the case of (Chomitz and Gray, 1999) implements a frictional surface function to estimate the cost of transportation at the cell rather than using distance to roads and distance to markets.

Spatial models are often used by geographers; Irwin and Geoghegan (2001) argued about the relevance of spatially explicit models on land-use change at highly disaggregated scales but criticized that most of these models lack an economic framework that allows establishing a causal relationship between individual choices and land-use change. Conversely, they highlighted the relevance of econometric models that allow identifying causal relationships but are limited in the use of spatially disaggregated data. (Chomitz and Gray, 1996) stated that the relevance of quantitative models in land use should use spatially disaggregated data and it must be assessed on an economic framework. This research combines both approaches, it is supported under the theoretical framework elaborated by (Chomitz and Gray, 1999), and it implements a fractional logit model to represent the shares of different land uses as Ortega-Pacheco et al. (2019), but rather than modeling at the municipality level, it incorporates spatially disaggregated data.

Recent literature has revealed that deforestation drivers change over time as the frontier evolves, and variables such as proximity to urban centers that used to boost the rates of deforestation have shown the opposite effect after the enforcement of the forest code (Wu & Sills, 2018). To the best knowledge of the author, very few studies have addressed the role of forest governance on the

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2 Note that tenure cost for the context of this research would depend on the risk of getting exposed to environmental sanctions for not comply with the existing regulations, and that is reflected under an enhanced forest governance regime.

effects of road network improvement on deforestation, and this research aims to contribute to filling this gap.

2.3 Forest governance

Forest governance has evolved from a centric structure in which governments exclusively regulated and enforced actions to a more complex multicentric structure that involves different stakeholders (Visseren-Hamakers and Glasbergen, 2007). As a result, forest governance is the result of diverse initiatives from businesses, civil society, private intersectoral partnerships (civil society and businesses), and public-private alliances.

The main legislation for forest protection in Brazil is the Brazilian Forest Code, which traces back to 1934. By 1965 Brazilian Forest Code initially required landowners to reserve in native vegetation at least 50% of their property land. The area to be protected was updated in 1996 to 80% for those properties located in the Legal Amazonia forest (Freitas et al., 2018). The amendments of the law 12.651 on forest code in 2012 incorporated some changes in the regulation that could have weakened the protection of forests. An amnesty was provided to those deforested areas before 2008; the former forest code stated that rural private properties could use up to 20% of the total land and set aside 80% as a "legal reserve." As the forest code is updated land users can reduce their legal reserve to 50% in those states that have already protected 65% of their territory in indigenous territories or conservation units (Freitas et al., 2018).

Brazilian regulations require all farms to protect and maintain forest areas known as legal reserves. The forest code restricts the deforestation inside private properties. Legal reserves are intended to regulate the sustainable use of natural resources, and to conserve and promote fauna and flora protection(Schmidt and McDermott, 2014)

The forest code restricts deforestation inside private properties. Legal reserve requirements are intended to regulate the sustainable use of natural resources, and to conserve and promote fauna and flora protection, while permanent preservation areas are areas established to secure freshwater protection, geological stability, and biodiversity (Schmidt and McDermott, 2014)

Under the 2012 Forest Code landowners who illegally deforested before 2008 can comply with the regulation by purchasing credits from landowners that have forested areas in excess of their legal reserves (Pinillos et al., 2021). These credits are known as Environmental Reserve Quotas (CRA) and their trade is regulated by the Rural Environmental License (LAR). The CRA works in the form of a Tradable Development Right (TDR). However, CRAs differ from TDR, because a CRA is an instrument that allows compliance of historical deficits of legal reserves rather than current or future deficits. (May et al., 2015). The update of the forest code in 2012 offered an amnesty that provided relief to all small and large properties from fines associated with illegal deforestation before July 22, 2008. After 2008, those who reduce native vegetation beyond the legal limit are required to restore those areas without the possibility of compensating by buying CRAs. Thus, landowners can contribute to the supply of CRAs, but this instrument can only be used to satisfy the compliance of historical rather than future deficits. Compensation can be done directly by purchasing permanent or temporary forest allowances on other property within the same biome to cover the deficit.

The creation of CRA instruments acknowledges that there are differential opportunities for land use and agricultural production, and it is less costly to conserve or restore areas with a lower potential economic return than areas with a higher value (May et al., 2015). Preconditions for the implementation of TDR mechanisms include property rights (or land tenure security), robust monitoring and enforcement, and low transaction costs. Land tenure security is a major obstacle for the implementation of the CRA (May et al., 2015)

Forest governance should be understood as a collective system in which government, private sector, market actors, and civil society share responsibility for forest and biodiversity conservation (Visseren-Hamakers and Glasbergen, 2007). The engagement of communities in the management of the forest is also a good practice.

Some initiatives have been proposed to assess the level of forest governance; e.g. the GFI framework from the World Resource Institute, and also Guides to Implement an Assessment such as the practical guide to data collection, analysis, and use for assessing forest governance from PROFOR and FAO (Cowling et al., 2014). However, there is no norm yet on how to measure it.

Chapter 1 introduced forest governance and Chapter 4 will provide an entire description of forest governance enhancement.

2.4 Brazil commitment to the Paris Agreement

At COP21, signers of the Paris Agreement agreed to take efforts to avoid an increase of global average temperature below 2°C with respect to the temperature pre-industrial levels and pursue efforts to limit the rise in temperatures to 1.5°C (Stiglitz et al., 2017). By 2019, 97 Parties have updated their Nationally Determined Contribution (NDC), and have indicated that will use Carbon markets and/or domestic carbon pricing to meet their NDCs(The World Bank, 2020). By 2020, 189 Parties have ratified the Paris agreement out of 195 parties that have signed. These countries represent 95% of global emissions (The World Bank, 2020).

World Annual Green House Gas Emissions are estimated at 11.4 Gt for the AFOLU sector (Stevanović et al., 2017). Current actions on climate change to achieve a temperature below 2~C are insufficient and NDCs to 2030 had to be revisited by 2020, however, not all the signing countries have revisited their NDCs (Stiglitz et al., 2017).

Despite the efforts on the ratification of the Paris Agreement, Parties have not reached a consensus on topics such as the transition of Kyoto protocol projects and credits. Some parties express their concerns about the full transition of the Kyoto Projects because it could undermine further actions taken to reduce emissions. This contrasts with the reliability of the UNFCCC decisions as the private sector has enrolled in Cleand Development Mechanism (CDM) projects under the Kyoto Protocol(The World Bank, 2020).

Brazil has demonstrated that it is possible to reduce emissions and also to boost its GDP, but also to take people out of poverty (Grottera et al., 2016). Between 2003 and 2014 about 29 million people were lifted out of poverty in Brazil("Poverty Reduction in Brazil | The Borgen Project," n.d.). Deforestation rates in Brazil had declined between 2004 and 2014; the opposite direction between economic growth and deforestation rates, reveal the relevance of the enhancement of forest governance. In this trend, policies that favor economic activities with low carbon emissions and the design of incentives, are key for inducing farmers and land tenures to contribute to the country's environmental goals. The interest in these mechanisms is rising, as the Brazilian government is in the exploratory phase of carbon pricing (World Bank, 2018). Furthermore, by 2019 the United Nation's Green Climate Fund approved to pay $96 million to Brazil for the first proposal on REDD+ (efforts to reduce emissions from deforestation and forest degradation), that accounted for a reduction of 19 million tons of emission in 2014 and 2015, compared to the rates in the period 1996-2010 (Sax, 2019).

Regardless the instrument used to promote a low-carbon economy, all of them are influenced by other policy actions like infrastructure investment. For instance, a large body of literature has assessed the effect of roads construction on deforestation and land-use change, and consequently the release of GHG.

2.5 Carbon pricing and carbon tax

Carbon pricing instruments help to overcome market failures on climate externalities (Stiglitz et al., 2017). The Intergovernmental Panel on Climate Change (IPCC) reviewed 100 studies on optimal carbon tax rates and estimated the average of a carbon tax rate at $12 per tCO2e, and a range between $3-$92/tCO2e (Metcalf and Weisbach, 2009). Worldwide there are more than 14,500 credit projects under 23 carbon mechanisms that are generating around 4 billion tCO2e of cumulative carbon credits, an equivalent of taking off the road 842 million passenger cars (The World Bank, 2020). Most carbon credits have been issued by CDM. ETS has the largest portion of the emissions covered by carbon instruments. It is also noteworthy that about 7MtCO2e out of 8,300 MtCO2e are covered by carbon prices that are less than $20/tCO2e (The World Bank, 2020). By 2017 85% of global emissions were not priced, and about three-quarters of emissions are priced at levels below $10/tCO2e. The main use of carbon credits is for companies to offset their obligations on emissions or meet voluntary commitments. The forestry sector is leading the carbon credits projects accounting for 42% of the total from 2015 to date. The private sector has been implementing at their decision-making internal carbon prices, as a measure to prepare for an eventual scenario in which governments put a price on carbon(Stiglitz et al., 2017).

The high-level Commission on Carbon Prices, supported by the Carbon Pricing Leadership Coalition (CPLP), concluded that the explicit carbon price level required to achieve the goals of the Paris Agreement is at least US$40–80/tCO2 by 2020 and US$50–100/tCO2 by 2030. However, these prices would require supportive policies that address market and government failures (Stiglitz et al., 2017). Carbon prices may vary across countries and low-income countries would require a lower price of carbon because complementary actions might be less costly, but the distributional and ethical issues may be more complex (Stiglitz et al., 2017)

There are two main characteristics of a cap and trade system and a carbon tax. Under a cap-trade system, carbon prices are uncertain: Prices of emissions rights training can vary, but there is some mechanism available that could help to narrow the range of prices. These systems include the banking of emissions over time, setting price floors, making post cap adjustments, among others (Stiglitz et al., 2017). Conversely, with a carbon tax, every ton of GHGs released needs to be paid at a fixed price in a given year (Stiglitz et al., 2017).

To mitigate the potential impact on economic activity that results from a carbon tax in the context of this research, Brazil could use financial instruments to reduce the upfront cost of mitigation actions. Alternatives such as interest rate subsidies or tax exemption to low-carbon enterprises (Stiglitz et al., 2017)

As part of the European Green Deal and aligned with the commitments from the Paris Agreement, the EU's long-term strategy is to be climate-neutral by 2050 with an economy with net-zero GHG emissions. The European Green Deal provides an action plan for achieving climate neutrality by 2050. This plan outlines the investments and financing tools needed but also considers an inclusive transition initiative called Just transition mechanism. This mechanism is funded with at least 100 billion (euros) for 2021-2027 and will provide technical assistance and financial support to the most affected on the transition to the Green Economy (Nelson, 2008) (European Parliament, 2020). International cooperation on carbon pricing could reduce the cost of implementing the NDCs by half to US$250 billion in 2030. Seven multilateral development banks are working together to support the design and operation of article 6 of the Paris Agreement. That article recognizes that Parties can engage in cooperative approaches to achieve their NDCs through the use of internationally transferred mitigation outcomes (ITMOs) (The World Bank, 2020).

The calculation of the optimal tax rate involves the prediction of effects of climate change, which are uncertain, and assumptions of economic and technological developments in the short and long run (Metcalf and Weisbach, 2009). Thus, an alternative to estimate carbon taxes relies on determining a set of taxes that would derive from a targeted level of GHG emissions reductions in the atmosphere. Setting the level of a carbon tax implies that for any given level of emissions, the tax rate should equal the marginal cost of producing one extra unit of emissions, and equivalent to the social marginal benefit of reducing one unit of emissions. The marginal benefit of abatement equals the marginal cost of abatement whenever the tax is at a fixed rate. Even though in this research it is recognized the relevance of considering all social costs and benefits to estimate the optimal tax rate, the main interest of using the tax/credit mechanism that will be implemented in Chapter 5 is to estimate the response to an eventual tax and how they would adjust their decisions on land use, and at what tax level, the emissions generated from road infrastructure could be abated or mitigated. A carbon tax can rely on existing fiscal tools, and it is easier to implement than a cap-trade system (Stiglitz et al., 2017).

The following papers describe the implementation of carbon taxes and their effect on deforestation and emissions:

Ralson and Barber (1984) reported by (O'Kelly and Bryan, 1996) examined the impact of three different taxation schemes on road development and the supply and demand of land production: incremental tax, ton-mile per vehicle-mile tax (fuel tax), and a commodity sales tax. The first has no effect on the cultivated area and does not affect transportation cost or market prices: the second, would reduce the cost-effectiveness for some farmers and so the land on cultivation diminishes; and the third, increases net prices at the port, which lead to land rents.

(Grottera et al., 2016). simulated the effect on a tax growing linearly from 0 to \$100/tCO2e to 2030 and \$150/tCO2e. Their results showed that under a high growth scenario there are labor productivity gains, and the revenue collected would allow investing in other development goals, such as social disparities, and so poorer households have higher income and consumption in the long run (Grottera et al., 2016).

(Kalkuhl and Ottmar Edenhofer, 2017) combined a Pigouvian perspective on the implementation of land taxes to target environmental externalities with factor taxation using the von Thünen in which they treat land allocation as endogenous. Some of their findings are that land taxes can increase overall economic output when marginal productivity of labor is lower in the agriculture sector than in the manufacturing sector, and the goods of these two sectors are substitutes, which implies there is an open economy.

(Stevanović et al., 2017) analyzed the impacts of incentives for producers (incentive base) and consumers (preference base) under mitigation policies on food prices. They estimate that food prices are likely to increase if incentive-based mechanisms are used; the protection of forests and the adoption of low carbon activities would increase land scarcity and production costs. Conversely, preference-based strategies could induce lower food prices, as there is a reduction in the consumption of waste and consumption of animal-based products, which decreases land scarcity and concentrate production to the most productive areas.

Taxes of agricultural land could be equivalent to a Pigouvian tax or subsidy that internalizes externalities of deforestation (Kalkuhl and Ottmar Edenhofer, 2017). Land taxes do not affect factor prices on labor nor capital, Land tax would induce a substitution of land for capital which would leave wages unaffected (Kalkuhl and Ottmar Edenhofer, 2017). Land taxes affect the assets portfolio because as they incentivize a transition from land assets to productive capital, which induces a capital insensitive production. However, even when this could lead to gains in welfare, those gross gains can be affected by a lower level of consumption(Feldstein, 1977). In the case of the carbon tax, it can be operationalized per unit of area by computing all GHG emissions released from a given unit of area at a given carbon price level in Chapter 5.

CHAPTER 3. ESTIMATION OF ACCESS COST

This chapter focuses on the estimation of "access cost". In the context of this research, access cost is a measure of the effort to transport an output (input) from (to) any location to (from) the market that can be reached with minimum travel time. Appealing to the seminal work of von Thünen referred in Chapter 2, it is assumed that access cost is an important determinant of land use in agriculture. That is, low access cost will tend to favor the production of bulky, perishable Crops such as fruits and vegetables, while high access cost will tend to favor forestry, which involves relatively little transportation of inputs and outputs. Evaluating access cost is key for this research as it can be used to reflect how changes in the road infrastructure relate to deforestation and land-use conversion. From a theoretical perspective, investments in roads improve the connectivity between production and consumption centers, facilitating access to technology, labor, and investments. In addition, these infrastructure improvements reduce the cost of inputs and increase the price of outputs at the farm-gate through the reduction in transactions (access) cost. Consequently, the potential return to various uses rises as land connectivity is enhanced, and the relative profitability of different land uses may be altered such that land conversion is expected among uses.

In this chapter, access cost is evaluated at a fine spatial scale across the Brazilian regions of Pará and Mato Grosso by modeling the entire region as a grid, dividing contiguous land areas into 5 arc-minute pixels for three different years: 2003, 2013, and 2018. The snapshot of the first two years (2003 and 2013) was used to estimate the role of access cost under the two forest governance policy regimes described later in Chapter 4, while the latter (2018) is employed in Chapter 5 to assess the role of a carbon tax/credit mechanism as a mitigation strategy for reducing the effect of roads on deforestation and GHG emissions. The selection of those years to model the two deforestation regimes was not determined by quantitative methods. Instead, it resulted from the observation of a set of favorable actions against deforestation and the years in which all those actions had been implemented. These actions promoted by the government, private sector, NGO's, and the international community will be explained in more detail in Chapter 4. At the time of initiation of this research, the year 2018 contained the latest data available on road infrastructure.

This Chapter is comprised of four sections. The first defines access cost in the context of this research and describes the treatment of the data used for its estimation; the second details the algorithm used for the estimation; the third presents the estimated access cost for the three periods (2003, 2013, and 2018); and the fourth section offers a discussion of the opportunities and critical control issues about this methodology.

3.1 Definition of access cost and the data needed for the estimation

Accessibility is often defined as the distance or effort required to reach one location of interest from another (Pozzi and Robinson, 2008), or in other words, how easy is to reach one desired destination from another (Forkenbrock and Weisbrod, 2001). In this research, these locations are called markets (sources of inputs and points of sale for outputs) and individual pixels (locations of land that can be used in various enterprises). The less time or effort to travel from any pixel to the closest market, the higher accessibility, and consequently, the lower access cost. Accessibility might be affected by different factors related to average travel time, reliability, physical land features.

The definition of market access has several possible interpretations such as the access of potential workers for jobs, and the access of businesses to both input suppliers and output customers. The lower the access cost the larger the benefit of businesses on the farm-gate price of inputs and outputs.

According to the National Cooperative Highway Research Program (NCHRP), changes in accessibility can be assessed using different approaches including 1) changes in travel cost and/or travel time, 2) changes in choices, and 3) changes in market. The estimation of changes in accessibility via changes in travel cost indicates how changes impact the use of transportation resources (Forkenbrock and Weisbrod, 2001). Changes in choices reflect how, within a targeted distance, one individual can have access to a diverse set of services such as health infrastructure, commerce, and recreation facilities within a target travel time. Estimation of changes in market reach relates to whether or not businesses increase the number of potential suppliers or customers within a specified time or practical operating constraint. Because the direct effect of roads is the alteration of travel cost from one location to another, this research uses travel cost as a measure of access cost to reflect changes in road infrastructure. More specifically the concept of person-hours per standardized load to move from the pixel to the market that is “nearest” in terms of travel time. Details are introduced in the next section.

Preparation of the data for the analysis:

Data sets on road infrastructure and land cover from Pará and Mato Grosso were used in the estimation of the access cost at the pixel level. Data description and sources of these two different datasets are presented in the Introduction Chapter (Chapter 1). The effort required to cross a given pixel depends on the “impedance” associated with the type of road or land use in that pixel. Impedance refers to judgmental estimates of the relative cost of transport (Chomitz and Gray, 1996) in which every pixel is assigned a value that represents the cost of moving through the pixel. Table 1.1 and Table 3.1 Impedance by road type and land use, respectively. When geo-referenced, these impedances can be visualized as a friction surface (Figure 3.1)

One challenge that needs to be addressed before using the road network data is that not all road infrastructure was geo-referenced. Data on the road network is available for all years starting in 1994 at the National Department of Infrastructure (DNIT), but data is publicly available in a geo-referenced format only after 2011. Data reported in a non-geo-referenced format, however, included attributes related to road quality for each highway that is part of the network, such as information on planned, dirt, in process of pavement, paved, in process of double lane division, and double lane roads.

The data that is not geo-referenced has information on the starting-point of each road (which is denoted as the kilometer zero), and its end-point (in which the assigned kilometer is equal to the length of the road). Data is organized into road segments, these are defined over the roads and are assigned an ID using the length from the origin of the road and the name of locations as a reference. For example, if within the first 10 kilometers of a road there were three different types of road quality attributes (quality A, B, C), there should be at least three contiguous road segments, say from kilometer “zero” to kilometer “p” the first segment with road quality “A”, then from kilometer “p” to kilometer “q” there is a second segment with road quality “B”, and from kilometer “q” to kilometer “ten” there is a third segment with road quality “C”.

To overcome that challenge, the geo-referenced road network was used to map the data that was not geo-referenced. Given that the geo-referenced data are also reported by road segments, the layers from geo-referenced roads were used to make the data of the road network before 2011 spatially available. Thus, characteristics such as IDs, names of locations, and length of the roads were employed to match the attributes from 2003 with the road network of 2013.

3.2 Estimation of access cost

Access cost for each pixel is estimated by using a least-cost path expansion algorithm embodied in the cost-distance function from Arc-GIS (ESRI, 2019) that computes how costly it is for a source to reach several pixels (Rivas, 2004). Two main elements are needed to implement this algorithm. The first is a set of impedances that indicates how costly it is to move across each pixel, and the second is a geo-referenced set of sources that represent the available markets that each pixel could potentially reach.

Access cost was defined as the minimum across neighboring markets of the travel time (person-hours per ten-ton load) required to reach the market by land or water, assuming that the path to market can traverse any pixel in the grid, regardless of the presence of a road. The methodology proposed here extends the work on accessibility and access cost by linking the travel time to a location of interest with the persons required to transport different commodities.

Travel time relies on the speed limits, the quality of the road surface, and the type of land use. The second column in Table 3.1 presents the speed of transit concerning road quality while the second column of Table 3.2 presents the time required to cross different land-use surfaces. The Brazilian speed limit on roads was assumed for paved roads (Ministério Da Justiça - Mj; Ministério Das Cidades - Mcidades, 2016). For those roads that are not paved, speeds were assumed to be 23 km/hour, and for earthen roads the speed was the same as gravel but was adjusted by seasonality factor that assumes these roads cannot be transited during the rainy season, which is 5 months. Thus, the 13.42 km/hour result from 7 months with a speed of 23 km and 5 months in which the speed is zero because it is impossible to transit those roads. For those road segments that are interrupted by a waterbody because of the absence of a bridge, it was assumed vehicles would use a ferry to cross that waterbody. The speed of a vessel in the water was assumed to be 20 km/hour which is equivalent to 3 minutes per km, but that time was adjusted by adding 20 minutes as a waiting time to the loading and unloading processes at the ferry.

The number of people needed to move a 10-ton load depends on the mode of transportation (e.g., trucks of varying sizes, cars, pack animals, etc.). Some of these are appropriate for all road types but not necessarily the most efficient while others are not suitable for some situations (e.g., trucks and cars cannot travel on forest paths while pack animals are not the most efficient means of transportation on paved roads). A cost function was constructed based on impedances that are assigned to every pixel based on the land use type as (Chomitz and Gray, 1996) but also by normalizing the access cost to a 10-ton load. That normalization was carried out to implement the algorithm efficiently and be able to standardize a common unit of transportation under the different methods of conveyance.

The following assumptions were made regarding the capacity of the vehicles used for transportation across land uses and road surfaces. One single capacity of transportation was established for road surfaces and land use types. For road surfaces a 10 ton truck type was selected for all road surfaces as most trucks of that capacity can transit those roads regardless of the road condition (i.e. from earthen roads to well-paved roads).

Carrying capacity on agricultural lands (pastures and Crops) was assumed to be 5 tons. The holding size of the bin in a combine is between 5 to 10.77 tons of soybeans (Edwards and Plastina, 2016), so the lower bound was used for agricultural lands. Areas in forest were assigned a carrying capacity of 0.1 tons. This because even in very remote areas, a horse can be used to transport goods, and horses can carry up to 20 percent of their weight ("Guidelines for weight-carrying capacity of horses | UMN Extension," n.d.).

Capacities and travel speeds were used in the normalization process. Provided that one single person was assumed to drive the vehicle across the land uses, one-hour transportation of a 10-ton load requires in this context the equivalent of 1, 2, and 100 persons on roads, pastures and Crops, and forest, respectively.

Recall that impedances represent the cost in time required for crossing one kilometer in a given pixel. Pixels that have roads on them have travel times that range between 0.67 to 4.47 minutes per kilometer depending on the quality of the road (Table 3.1), and pixels with no roads have travel times that range between 2 to 60 minutes per kilometer, depending on the type of land cover (Table 3.2). The potential markets in the region include all the municipalities from Pará and Mato Grosso that have more than 100,000 people (Table 3.3).

Table 3.1 Impedance by road type*

Description	Speed (km/h)	Travel time (min/km)	Travel time adjusted by carrying capacity (person hour load/km)
Double lane highway	90	0.67	0.011
Paved highway	80	0.75	0.013
Double lane	60	1	0.017
paved	60	1	0.017
Unpaved: Gravel road	23	2.61	0.043
Unpaved: Earthen road	13.42	4.47	0.075
Waterbody crossing (no bridge)	20	23	0.383
In process of double lane	13.42	4.47	0.075
In process of pavement	23	2.61	0.043
In process of gravel	13.42	4.47	0.075

*Constructed based on (Ministério Da Justiça - Mj; Ministério Das Cidades - Mcidades, 2016)

Table 3.2 Impedance by land type*

Land use type	Travel time (minutes/km)	Normalized carrying capacity with respect to a load of 10 tons	Travel time adjusted by carrying capacity (minutes load/km)	Travel time adjusted by carrying capacity (person hour load/km)
1. Forest				
Forest Formation	60	0.01	6000	100
Savanna Formation	36	0.5	72	1.2
Mangrove	60	0.01	6000	100
Forest Plantation	60	0.01	6000	100
2. Non Forest Natural Formation				
Wetland	36	0.01	3600	60
Grassland	36	0.5	72	1.2
Other Non Forest Natural Formation	36	0.01	3600	60
3. Farming				
Pasture	36	0.5	72	1.2
Annual and Perennial Crop	36	0.5	72	1.2
Semi-perennial Crop	36	0.5	72	1.2
4. Non vegetated area				
Urban Infrastructure	2	1	2	0.03
Mining	24	1	24	0.4
Other Non Vegetated Area	24	1	24	0.4
5. Water				
River, Lake and Ocean	3	1	3	0.05

*Constructed based on (European Commission, n.d.) and Nelson (2008)

Table 3.3 Major cities in Pará and Mato Grosso

STATE	CITY	POPULATION
MATO GROSSO	Cuiabá	601,120
MATO GROSSO	Várzea Grande	280,580
MATO GROSSO	Rondonópolis	223,630
MATO GROSSO	Sinop	118,540
PARÁ	Belém	1,479,970
PARÁ	Ananindeua	529,290
PARÁ	Santarém	223,120
PARÁ	Marabá	222,680
PARÁ	Parauapebas	187,680
PARÁ	Castanhal	177,870
PARÁ	Marituba	130,160
PARÁ	Tucuruí	108,180

Source: Mato Grosso (State, Brazil) - Population Statistics, Charts, Map and Location (citypopulation.de)

Impedances reflect the cost of moving one load of output through a pixel and are accounted for in person-hours per load. The size of the load was standardized to 10 tons, which is a suitable size for transporting diverse commodities in the region from cattle to soybeans. For example, it can be represented as a fraction of a 40-ton soybeans truck haul, or as a 10-ton truck loaded with between 17 to 22 head of cattle.

A friction surface was used for that purpose and speeds on the pixel were assigned depending on whether a road passes across a pixel or not. For those pixels that have a road on them, speed limits based on the Brazilian law 13,281 of 2016 regarding the transportation code on urban and non-urban areas were used to reflect impedance values. For other pixels, impedances were estimated using the type of land cover and carrying capacities of potential means of transportation given the land cover.

Geo-referenced data on elevation is often used as a multiplier factor for adjusting the impedance values to indicate that a larger slope would represent a higher effort for moving through a pixel (Ulimwengu et al., 2009). This research follows the approach proposed by Van Wagtendonk and Benedict (1980) but given that the impedances are defined as person hours per kilometer (instead of km/h) the multiplier factor is adapted as follows, where v_0 is the base travel speed, k is a constant equal to 3 for the uphill and downhill slope on travel speed (Ulimwengu et al., 2009), and s is the slope gradient in meters (i.e. a 1:0.2 slope means that for every meter along the ground the hight increases by 0.2 meters) :

$$v = v_0 * 1/e^{(-ks)}$$

Equation 3.1 Multiplier factor friction surface

Recall that in the description of the data, it was stated that data sources were at a different resolution: data on land characteristics was available at 5-arcminute resolution while the data on the land cover was at a 30 square meter resolution. Because the analysis is constrained by the lower resolution, the land cover data was aggregated to the lower resolution of the land characteristic data. Thus, once the friction surfaces are constructed, these were aggregated to a 5-arc minute resolution of approximately 9.2 km^2 using the mean of the higher resolution sub-pixels contained in the lower resolution pixel.

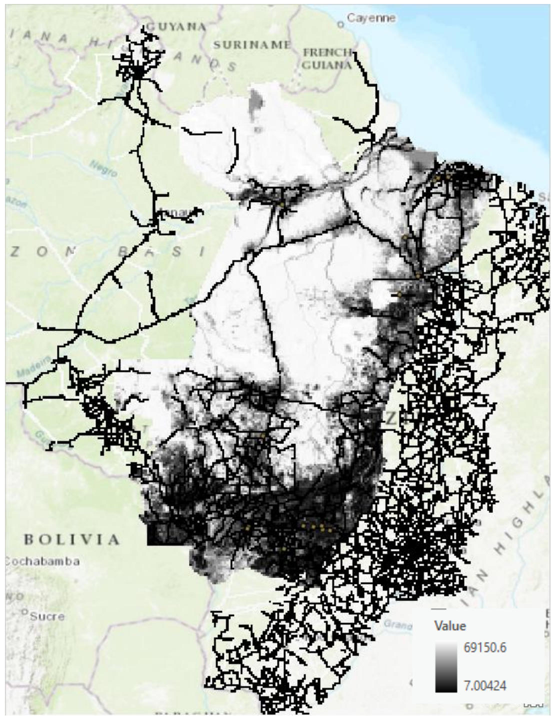


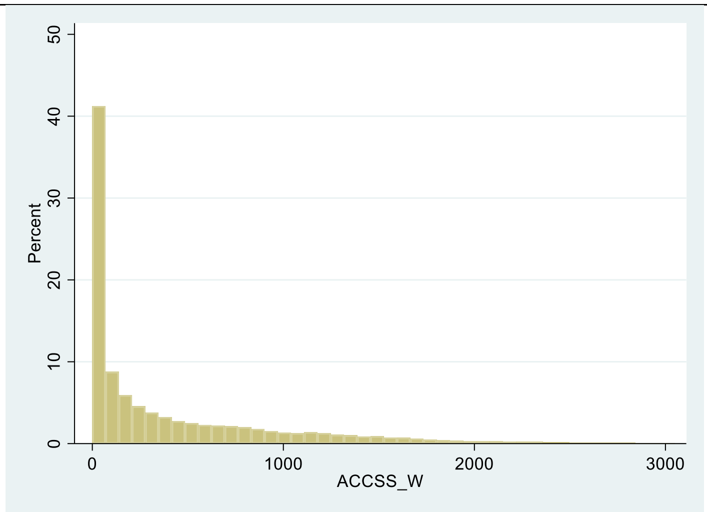
Figure 3.1Friction surface year 2013
*Travel cost to cross one pixel with a 10-ton load (in person-hours)

<u>Algorithm for calculating access cost to markets</u>

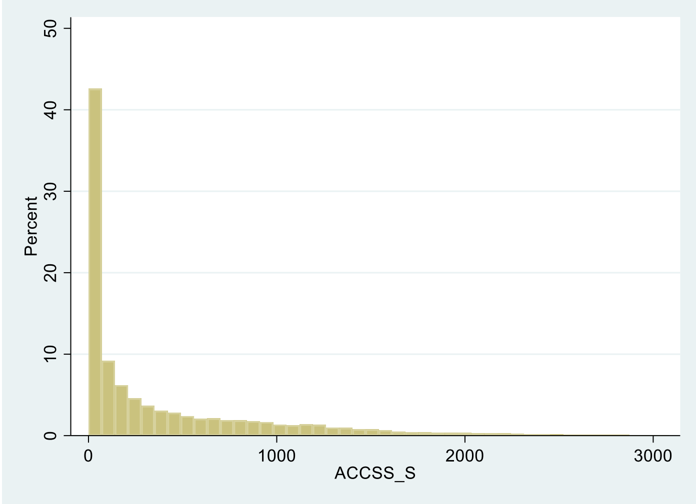
The minimum access cost to a market is calculated in ArcGIS Pro using the cost distance function. That function applies the least cost-path algorithm due to Dijkstra (Dijkstra, 1959). The calculation of the minimum access cost to a market from each pixel is essentially a dynamic programming approach. For the computation, each cell on a grid is assigned with an impedance that represents how costly it is to move across that cell, and the potential markets are geo-referenced. The assignation of the least expansion path performs backward, starting from the cells adjacent to the markets and the cumulative access cost to the market from the pixels in the market is initialized to zero for each of the available sources. Each source acts as an active cell that has different alternatives for expanding its path, but the expansion of an active cell only occurs when the cumulative cost of moving to a neighboring cell takes the lowest value among all expansion alternatives from other active cells. Then the cumulative access cost is recalculated for each pixel as the minimum across all adjacent pixels of the impedance of the pixel plus the access cost of the adjacent pixel. At every iteration, the active cells are replaced for those that provided the least expansion cost for each source in the previous iteration. At some point, as the cumulative cost keeps increasing, those active cells and their neighboring cells that were not an option in past iterations would offer a cumulative expansion cost lower than the current expansion path, and then the expansion path is relocated to that less costly alternative. This calculation is performed repeatedly until the cumulative pixel-level access costs converge, which means that each of the pixels in the grid has been reached by one of the sources on their least-cost expansion process. Details of the cost distance function may be found in ESRI (2019).

3.3 Results

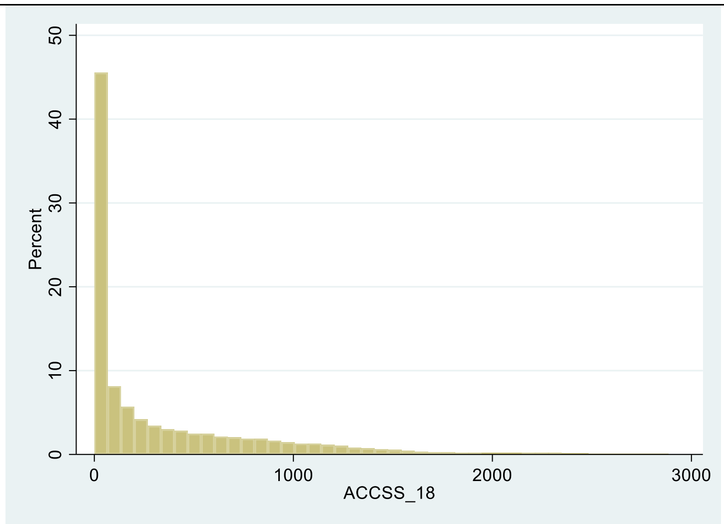
Estimated access cost data is right skewed for all the three years (Figure 3.2). However, the values reported per percentile were different, being the latest year the one with the lowest reported values for the same percentile. For the year 2003, 40% of the cells reported an access cost of less than 61.48 person hours per load, while cells with an access cost between 61.48 and 784.76 represented another 40%, and all the cells with an access cost value above that range the remaining 20%. For the years 2013 and 2018 values on access cost below 41.75 and 56.50 represented 40% of total observations, respectively; the same downward tendency was observed for percentile 80 of the access cost distribution for which values were reported below 748.09 and 673.75.



Panel A: Access cost 2003



Panel B: Access cost 2013



Panel C: Access cost 2018

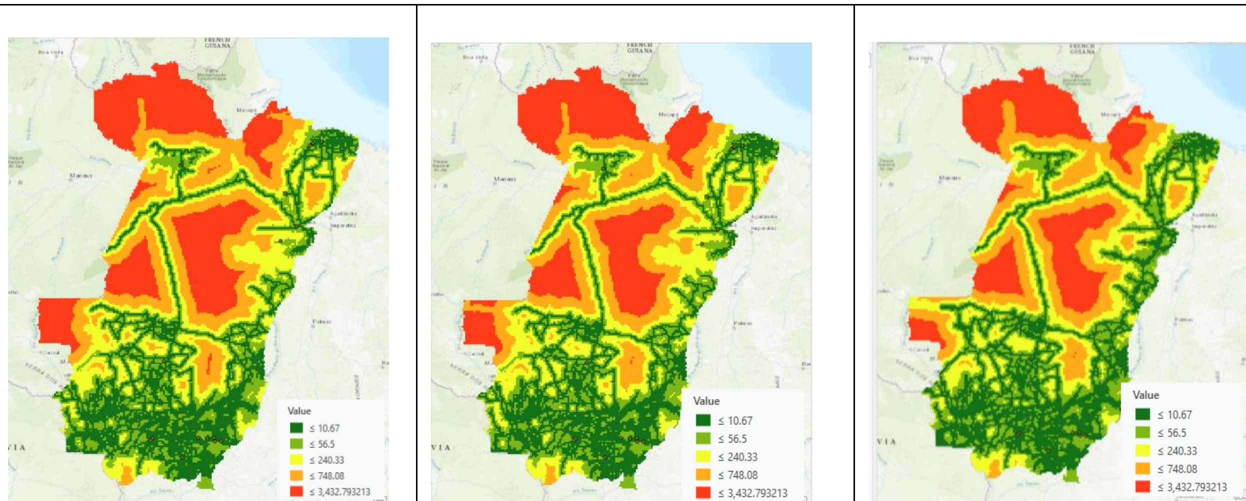
Figure 3.2 Histogram access cost Pará and Mato Grosso
* Panel A (year 2003), Panel B (year 2013), and Panel C (year 2018)

The official road network of Pará is concentrated in the northeastern region of the state where most of the main cities are located, while in Mato Grosso roads are spread across the state. Access cost results are consistent with the road network data and location of main cities. The estimated access cost for Pará and Mato Grosso is presented in

Figure 3.3. The cost to reach the closest market ranged between 0.011 to 3084.294 person-hours per 10-ton load. The darkest green areas are those with the lowest access cost and the darkest red are those with the highest access cost. As expected, those areas along a road have a relatively lower access cost, and changes in road infrastructure (improvement in quality or construction of new roads) reflect a drop in access cost across years. For instance, access cost improved for the less connected areas along the corridor over the BR165 that connects Sinop (Mato Grosso) with Santarem (Pará) as their access cost to transport a 10-ton load to the closest market dropped from between 6 hours and less than 24 hours to less than 6 hours between 2003 (
Figure 3.3 -PanelA) and 2018 (
Figure 3.3 – Panel C). A summary of statistics on how access cost changes between periods is presented in (Table 3.4), the mean of access cost across pixels decreased between periods. It moved from 410.44 person-hours in 2003 to 554.57 person-hours in 2013, and then to 351.23 in 2018.

Table 3.4 Summary of statistics Access Cost

Year	Obs	Mean	Std. Dev.	Min	Max
2003	25,421	410.55	562.44	0.01	3050.72
2013	25,421	392.24	554.57	0.01	3084.29
2018	25,421	351.23	507.02	0.01	2952.20



Panel A: Access cost 2003 | Panel B: Access cost 2013 | Panel C: Access cost 2018

Figure 3.3 Access cost for Pará and Mato Grosso across years

*Access cost in person hours. Panel A (year 2003), Panel B (year 2013), and Panel C (year 2018)

The decreases in access cost reflect the changes in the effort required to reach the closest market as a result of road infrastructure improvement. Large investments have taken place in Brazil to boost infrastructure. The Brazilian Development Bank (BNDES) more than double its financial support of infrastructural projects from US$22 billion to US$ 53.2 billion (Amann et al., 2016). In 2007 the Growth Acceleration Program (PAC) for the provision of infrastructure, including roads, was launched. This program, initially scheduled for four years, was extended to a second four year term. Particularly, the improvement of the road network infrastructure in Pará and Mato Grosso is reflected in the increase in the paved road network from 4,663 to 6,742 kilometers between 2000 and 2018

Access cost has declined across years. Figure 3.4 presents access cost data for 2013 as a 45-degree line colored in orange, while access cost for 2003 and 2013 are represented in blue and orange color. It can be appreciated that a cloud of data in blue appears above the 45 degree indicating that those pixels had a higher access cost in 2003 than in 2013. Conversely, a cloud of data in grey appears on or below the 45-degree line indicating that access cost either remained constant or fell between 2013 and 2018. Note that the decline between 2013 and 2018 was more than twice the decline between 2003 and 2013 but over half as many years. On average there was a drop in access cost of 18 person-hours from 2003 to 2013 (a 4% drop), while between 2013 and 2018 the drop was of 41 person-hours on average (a 10% drop). The largest reductions per pixel in access cost for the period between 2003 and 2013 happened for pixels within the range of 250 to 2000 person-hours of the 2003 data, with the largest single pixel decline being 369 person-hours.

The largest reductions per pixel in access cost from 2013 to 2018 were reported for those pixels in 2013 that ranged between 1,100 and 2,200 person-hours, in which the largest single pixel decline was from 1,186 to 369 person-hours. Note that those reductions in access cost happened at the frontier of human development,[3] which is represented by the yellow color but also in remote areas beyond the frontier orange color in

[3] Frontier is referred in this research as a region with a scarce population, whose economic potential is unexploited, and that is in the edge of human development.

Figure 3.3.

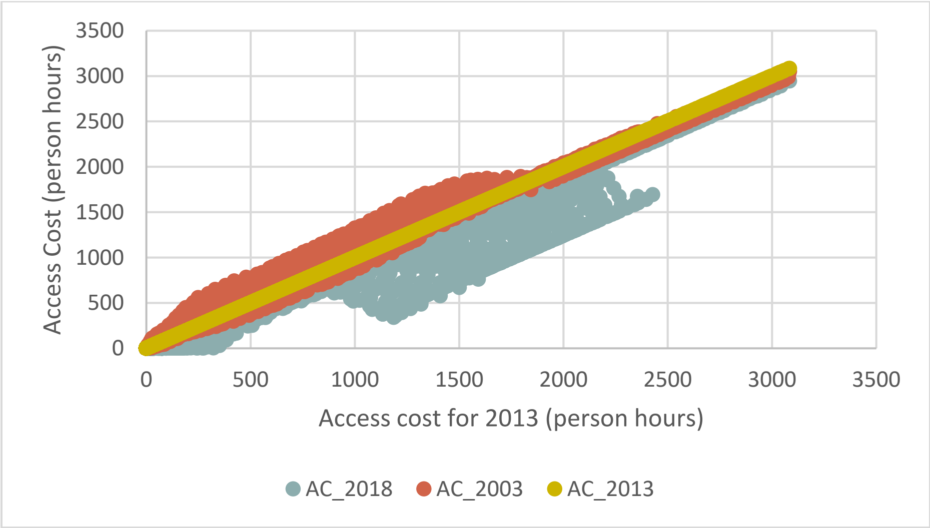


Figure 3.4 Access cost relative to 2013

3.4 Opportunities and critical concerns

The approach employed for estimating access cost allowed a spatial assessment of changes in road infrastructure in terms of the effort needed to transport an equivalent weight. Estimation of access cost was carried out for three different years (2003, 2013, and 2018) from every pixel to the nearest market in terms of time to transport a 10-ton load. This technique also generation of maps that graphically depict the regions in which the major changes in access cost are have happened. The most notable changes in access cost occurred in those regions that belong to the frontier, which are those areas characterized for not being well connected, having a low population density, and with relatively undeveloped economic activity.

Access cost information generated in this chapter will be used in the following two chapters to evaluate the effect of access cost derived from road infrastructure on land-use change and to implement a carbon tax/credit that would influence decisions at the parcels.

This is a relevant contribution as the evaluation of access cost is of interest to diverse agents. Access cost is likely to affect citizens' ability to reach new services, goods, and jobs; a decrease of access cost would allow farmers to increase their welfare as they have better access to markets for inputs and outputs; and policymakers can use this measure of access cost to estimate the effect of projects or programs on economic activity, as well as environmental impacts.

Most data on road infrastructure used in this chapter to compute a measure of access cost relates to the official Federal road network. Unofficial roads were not considered in this analysis, but these unofficial roads are likely to have an impact on land-use change, and it will be important to address them in further research. The main challenge for this is the availability of data that is scarce or unavailable. However, there are remote sensing approaches that can be used to generate that data. Brandão and Souza (2006), mapped 25,195 km of unofficial roads for the Central-West region of the State of Pará during three five-year periods between 1985 to 2001. They used land satellite images and tested three different approaches including manual digitalization (visual interpretation) and two automated techniques for road extraction. The automated approaches seemed to work well in forested areas, but the speed gained in the automated process sacrifices consistency and accuracy, providing false signals as bare soil segments can be identified as roads. Based on their work, they suggest 2,290 hours would be necessary to map the entire road network for the Brazilian Amazon.

Another challenge that needs to be addressed is that railroad connectivity is not included in this measure of access cost. Future work needs to address this intermodal form of transport, even though road transportation still represents about 60% of total freight.

While the approach presented in this Chapter is deliberately focused on Pará and Matto Grosso, the techniques for evaluating access cost are applicable to infrastructure developments in other parts of the world. For example, the Biden administration in the United States has recently proposed a $2 trillion infrastructure development plan. Not all of that is focused on the transportation infrastructure but much of it is. While the concerns in the United States are less about environmental impacts of infrastructure than they are in Brazil there is interest in understanding the benefit/cost relationship embedded in the Biden plan and the access cost measure developed in this chapter could provide a means of measuring increased economic activity at the local level due to improvements in the transportation infrastructure. Many other similar applications exist for this approach in facilitating the estimation of benefit/cost relationships for public policy decision making.

CHAPTER 4. ASSESSING CHANGES IN LAND USE DERIVED FROM CHANGES IN ROAD INFRASTRUCTURE

In the previous chapter, a methodology to estimate access cost was presented and used to estimate the cost in person hours to reach the closest market from each pixel in the Mato Grosso and Pará regions of Brazil for three years: 2003, 2013, and 2018. This chapter builds on those results. In the previous chapter, road infrastructure was linked to the concept of access cost, and in this chapter a land use model is implemented using access cost as one of the explanatory variables to assess the effect of road infrastructure on deforestation. In addition, the model presented in this chapter allows a comparison of the effect of access cost under two forest governance regimes. Because this model is able to predict changes in land use due to changes in road infrastructure, it will be used in a subsequent chapter to estimate the impact of road infrastructure enhancement on deforestation and to assess the implementation of a carbon tax/credit mechanism to mitigate the effects on deforestation and GHG emissions. This Chapter is organized in four sections: the first presents the assumptions regarding forest governance and the assignment of different regimes to two different periods, the second describes the methodology, the third summarizes the results, and the fourth offers a discussion of the findings.

4.1 Description of Forest Governance

Law enforcement, establishment of protected areas, and payments for environmental services are policies associated with lower deforestation. Brazil uses a mix of these policy instruments. These include a regulatory framework (Forest Code), law enforcement, protected areas at departmental and national level, territories reserved for indigenous people, forest monitoring systems, and payments for environmental services (Tacconi et al., 2019).

Native vegetation removal in Brazil is legal only if it has been authorized by a government environmental authority. These authorizations can only be granted to private landholders and to public lands assigned to protected areas and agrarian reform settlements (Assunção et al., 2013). Private landholders also need to adhere to the forest code which states that only 20% of total area can be deforested in the Amazonía, while the remaining 80% must be protected. Forest clearance that does not comply with the code is considered illegal (Assunção et al., 2013). Amendments of the Forest Code in 2012, state that the private legal reserves of forest could be reduced up to 50% in those states that have already protected at least 65% of their territory. (Freitas et al., 2018).

The two main reasons behind the Brazilian Amazon deforestation are agricultural land conversion and illegal "land grabbing" as forest clearing is often used to claim tenure status over the land (Assunção et al., 2013). Even though the Forest code was established in 1965 and then updated by the Federal Law 12651 in 2012, it was not until 1998 that Environmental Crimes Federal Act No. 9605 was established as the legal framework to prosecute environmental crimes, and later that framework was updated in 2008 by the Environmental Administrative Infraction Decree No. 6514 (Tacconi et al., 2019). As the 1998 law of environmental crimes was enacted, it allowed structuring environmental infractions and legal paths to apply administrative sanctions (Assunção et al., 2013). The Brazilian Institute for Environment and Natural Resources (IBAMA) was responsible for monitoring deforestation and coordinating law enforcement at the state level from their local offices. This comprises both investigation of infractions and application of administrative sanctions (Assunção et al., 2013).

Before 2004, IBAMA's actions relied on intelligence and on its capacity to anticipate spatial deforestation, intelligence, and reports from a hotline (Assunção et al., 2013). The lack of rapid response allowed violators to move heavy equipment used for clearing forest lands to other areas before IBAMA could take action in response to infractions (Assunção et al., 2013).

The ability of the authorities to respond to environmental crimes changed after the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon -PPCDAM was implemented in 2004. This plan allowed for integrated actions across government institutions for forest protection and focused on three objectives: permanent monitoring, environmental enforcement, and land tenure regularization. A relevant innovation was the implementation of the Real-time System for Detection of Deforestation (DETER), that allowed identification of deforestation hotspots for immediate action. These real-time alerts accelerated the enforcement of forest protection. Because heavy equipment is not moved until all area is cleared, real-time information increased the probability of interdicting violators on-site. Law enforcement officers then destroyed the associated machinery and equipment. These are generally high-cost assets and their potential seizure leads to higher expected costs associated with illegal deforestation (Assunção et al., 2013).

DETER allowed IBAMA to inform their decisions on law enforcement against offenders and issue them civil and criminal charges (Assunção et al., 2013). Also, fines were issued to those violators along with some administrative actions such as embargoes that restricted landholder access to rural credit and the confiscation or destruction of products and equipment used for deforestation.

Annual deforestation rates had a growing tendency until 2004, in part due to the lack of an ability to enforce the existing regulations. The largest drop in deforestation rates in Brazil occurred between 2004 and 2014. Forest governance during this period was not limited exclusively to government policies or actions, but it comprised efforts from diverse stakeholders that complemented the PPCDAM. These actions included but were not limited to the promotion of incentives for forest conservation, the soybean and beef voluntary moratoriums, designation of protected areas of ecological interest as well as of indigenous populations, and law enforcement. In 2008, a group of 36 priority municipalities that represented 45% of total deforestation in the preceding year was targeted and marked as blacklisted by the Brazilian Ministry of Environment. One year later, the list expanded by 9 additional municipalities, and by 2011 the list increased to 56 out of 547 in the Amazon Biome (Assunção and Rocha, 2019). In addition to a more strict system of monitoring and environmental law enforcement, credit access in these municipalities was limited to only those properties that complied with the environmental regulation (Massoca et al., 2017). This credit access became an incentive for landholders to register in the Rural Environmental Registry (Cadastro Ambiental Rural - CAR).

The private sector played a determinant role in reducing deforestation rates: farmers are five times more likely to violate a governmental policy than the soy moratorium (Gibbs et al., 2015). The soy moratorium consisted of major soybean traders who agreed not to purchase soy grown in areas deforested after July 2006 in the Brazilian Amazon. Before the agreement, nearly 30% of soybean expansion was in deforested areas, while after the moratorium, the expansion on deforested areas dropped to less than 1% by 2014 (Gibbs et al., 2015). This initiative along with pressure from the consumers and international environmental organizations inspired the four largest producers and traders of the beef and leather sector to adopt a similar model in 2009. The beef moratorium helped to reduce deforestation because, when market conditions were favorable for expansion, ranchers opted to expand their production in areas already in pasture rather than clearing forest (Macedo et al., 2012).

In 2008, the Amazon fund was created by the Brazilian Development Bank (BNDES). Following the Decree 6,527/2008, this fund was "intended to provide non-reimbursable funds to investments in actions that prevent, monitor, and avoid deforestation and help promote conservation and sustainable usage of the Forest in the Amazon Biome". Norway, as its major donor, agreed to provide up to $1 Billion for this purpose that supported programs for Reducing Emissions from Deforestation and Forest Degradation (REDD+) (Birdsall et al., 2014). To date, this fund has supported 102 projects and has disbursed $534 million whose main themes have been classified into indigenous lands, conservation areas, Rural Environmental Registry (CAR), Settlement, and to combat of illegal fires ("Amazon Fund," n.d.).

As discussed, Forest governance cannot be considered as a single set of policies from the government. Rather, it must involve voluntary actions from the private sector and involve the international community for the adoption of mechanisms on payments for conservation. The peak of deforestation rates in 2004 marked a milestone in terms of forest protection that coincided with the implementation of the PPCDAM. Consequently, for this research, the year 2003 is treated as the last year under a weaker forest governance regime. As discussed in this section, different actions have been implemented gradually between 2004 and 2012 to preserve forests, and thus the year 2013 is considered in this research to be representative of an enhanced forest governance regime. In fact, 2013 had one of the lowest deforestation rates in the last 30 years. Unfortunately, there was a kink in 2015 in deforestation rates and annual deforestation rates have been increasing since then.

4.2 Methods

This chapter focuses on estimating the effect of road infrastructure on land-use change and providing empirical evidence of the role of forest governance in altering the impact of road infrastructure development on deforestation. The following two specific hypotheses are tested. The first of these null hypotheses is: market access improvement through road infrastructure does not induce higher deforestation; and the second is stated as: forest governance has no effect on land-use conversion due to market access changes. Even though there is vast empirical evidence on the first hypothesis, testing this hypothesis allows embedding this research in the von Thünen style framework, in which lower transportation costs are key determinants of land use rents (Sprawl and Sinclair, 1967). The second hypothesis evaluates whether forest governance plays a role in diminishing the rates of deforestation derived from road development. The empirical analysis behind the identification of the effect from the two forest governance regimes on deforestation relies on the assumption that higher governance and enforcement lead to a higher probability of punishment, increasing the expected cost of unauthorized deforestation activities. As a measure of access, a pixel-level variable is constructed to serve as a proxy for how costly it is to reach the closest market from every pixel (See Chapter 3).

Because the variables are available at different spatial resolutions (dimension of the cell size representing the area on the ground, (ArcGIS, n.d.), the size of a pixel cell is limited by the data observed at the lowest resolution. For instance, land cover is available at 30mx30m but soil characteristics are available at a resolution of 5 arc-minute (approximately 9.2 km^2). Thus, the pixel size or unit of analysis used in constructing the data was 5 arc-minute. The implementation of land shares Sh_{ij} in the analysis allowed use of the additional information from the land cover variable that is available at the higher resolution. The land shares would refer in this model to the proportion of land cover *j* within the pixel i, and the proportion is given by the total of cells of a smaller size (30mx30m resolution) geographically contained in the 5 arc-minute pixel. This is represented in Equation 4.1 where A_{il} refers to the area of the cell *l* (30mx30m) contained in pixel *i* (5 arc-minute) and I_{jil} is an indicator variable that takes the value of one when the cell *l* is in land use *j*. It is noteworthy to mention that the sum of the shares in a given pixel must equal one.

$$Sh_{ji} = \frac{\sum_l A_{il} * I_{jil}}{\sum_l A_{il}}$$

Equation 4.1 Land Shares at the pixel

A fractional multinomial logit land-use model is fitted with explanatory variables on market accessibility cost, previous land use shares, soil characteristics, and land protection status that are described in Chapter 1 (Introductory Chapter) and summarized in

Table 4.1. The functional form of this model comes from the work of Mullany (2015) as an extension of the fractional regression methodology proposed by Papke and Wooldrigde (1996). The expected value of the share of land in pixel *i* devoted to land use j is denoted by $E[Sh_{ij}|X_i]$ (Equation 4.2). It relies on characteristics at the pixel level (X_i) such as agronomic constraints, access cost, and protection status. As in the case of the multinomial model, the model is under-identified unless the coefficients of one of the categories are known (Nelson & Hellerstein (1997); thus $\beta 1 = 0$ is imposed for all the coefficients of the land share in Forest to identify the model's parameters (Equation 4.3). Because the coefficients for the explanatory variables of land share Forest are normalized, the reduced form that supports estimation can be represented as the log of a relative proportion ratio denoted by β_j (Equation 4.4)

$$E[Sh_{ij}|X_i] = \frac{e^{\left(X_i'\beta_j\right)}}{1+\sum_{j=2}^{n} e^{\left(X_i'\beta_j\right)}}; \text{ j=1,…,n}$$

Equation 4.2 Expected Land Shares. Fractional multinomial logit model

$$E[Sh_{ij}|X_i] = \frac{1}{1+\sum_{j=2}^{n} e^{\left(X_i'\beta_j\right)}}; \text{ j=1}$$

Equation 4.3 Expected Land Shares for Forest. Fractional multinomial logit model

$$\log\left(\frac{Sh_{ij}}{Sh_{i1}}\right) = log\left(\frac{e^{\left(X_i'\beta_j\right)}}{1+\sum_{j=2}^{n} e^{\left(X_i'\beta_j\right)}} / \frac{1}{1+\sum_{j=2}^{n} e^{\left(X_i'\beta_j\right)}}\right) = X_i'\beta_j$$

Equation 4.4 Log relative land share ratio

The influence of the explanatory variables on the *log relative land share ratio* (beta coefficients) is obtained using a quasi-maximum likelihood estimation represented in Equation 4.5, where F_{ij} stands for the observed land fraction in use *j* at pixel *i*.

$$QMLE = \sum_{i=1}^{n} \sum_{j=1}^{n} F_{ij} * logE[Sh_{ij} | X_i]$$

Equation 4.5 Quasi-maximum likelihood

The land-use model is estimated using STATA for two different years; 2003 and 2013. As discussed previously, these two years are distinguished by the degree of forest governance regime: weak and strong, respectively. Explanatory variables in this framework include a 5-year lagged land use that represents inertia in land use (that is, changing land use is a costly investment and tends not to happen in the absence of economic incentives to do so – including lagged land use controls for this stickiness), soil characteristics, access cost, and whether the land is a "protected area" such as lands belonging to indigenous peoples and areas designated as protected at the departmental and national level such as national parks, biological reserves, national forests, wildlife reserves, among others. A five-year lag was chosen somewhat arbitrarily. However, because land use across much of the landscape under examination changes extremely slowly, choosing a lag length shorter than this runs the risk that past land use in almost all pixels would be unchanged, providing little information about how access cost and governance impact land use.

Setting the lag greater than five years runs the risk of encompassing past information that is driven by a different forest governance regime. Failing to account for this dynamic could lead to inefficient and inconsistent estimates of the other model parameters. The complete list of explanatory variables used in the model is presented in

Table 4.1, and descriptive statistics for the variables are presented in Table 4.2 and Table 4.3, respectively.

Table 4.1 Notation for explanatory variables

Explanatory variables ("Weak" forest governance regime)	Explanatory variables ("Strong" forest governance regime)	Description
CROP_LAG_W	CROP_LAG_W	Lagged pasture land-use share (Weak/Strong forest governance regime)
CROP_LAG_W	CROP_LAG_W	Lagged Crop land-use share (Weak/Strong forest governance regime)
SIL_LAG_W	SIL_LAG_W	Lagged silviculture land-use share (Weak/Strong forest governance regime)
OTH_LAG_W	OTH_LAG_W	Lagged other land-use share (Weak/Strong forest governance regime)
ACCSS_W	ACCSS_W	Access cost (Weak/Strong forest governance regime)
NUTC_W	NUTC_W	Indicator variable for more than moderate restrictions in soil nutrient content (Weak/Strong forest governance regime)
OXGNC_W	OXGNC_W	Indicator variable for more than moderate restrictions in soil oxygen availability (Weak/Strong forest governance regime)
NTRNC_W	NTRNC_W	Indicator variable for more than moderate restrictions in soil nutrient content (Weak/Strong forest governance regime)
WORKC_W	WORKC_W	Indicator variable for more than moderate restrictions in soil oxygen availability (Weak/Strong forest governance regime)
INDGN_W	INDGN_W	Indicator variable for land granted to indigenous groups (Weak/Strong forest governance regime)
PRONAL_W	PRONAL_W	Indicator variable for protected areas at the national level (Weak/Strong forest governance regime)
PRODPT_W	PRODPT_W	Indicator variable for protected areas at the state level (Weak/Strong forest governance regime)

Table 4.2 Descriptive statistics weak forest governance regime

VARIABLES	(1) N	(2) mean	(3) sd	(4) min	(5) max	(6) skewness
OTH	25,421	0.0976	0.170	0	0.997	2.289
FORST	25,421	0.683	0.330	0	1	-0.633
CROP	25,421	0.0274	0.111	0	0.955	5.059
PAS	25,421	0.192	0.239	0	0.997	1.145
SIL	25,421	0.000113	0.00386	0	0.375	67.60
OTH_LAG_W	25,421	0.0988	0.175	0	1.000	2.199
CROP_LAG_W	25,421	0.0191	0.0889	0	0.939	5.983
PAS_LAG_W	25,421	0.161	0.213	0	0.998	1.395
SIL_LAG_W	25,421	0.000149	0.00404	0	0.275	40.81
ACCSS_W	25,421	410.6	562.4	0.0113	3,051	1.778
NUTC_W	25,421	0.949	0.221	0	1	-4.068
OXGNC_W	25,421	0.119	0.324	0	1	2.355
NTRNC_W	25,421	0.799	0.401	0	1	-1.488
WORKC_W	25,421	0.209	0.407	0	1	1.429
INDGN_W	25,421	0.201	0.401	0	1	1.492
PRONAL_W	25,421	0.101	0.302	0	1	2.640
PRODPT_W	25,421	0.0671	0.250	0	1	3.459

Table 4.3 Descriptive statistics strong forest governance regime

VARIABLES	(1) N	(2) mean	(3) sd	(4) min	(5) max	(6) skewness
OTH	25,421	0.0897	0.168	0	1.000	2.415
FORST	25,421	0.652	0.330	0.000311	1	-0.422
CROP	25,421	0.0456	0.135	0	0.962	3.779
PAS	25,421	0.213	0.247	0	0.991	0.979
SIL	25,421	0.000340	0.00502	0	0.310	32.26
OTH_LAG_S	25,421	0.0948	0.168	0	1.000	2.398
CROP_LAG_S	25,421	0.0362	0.124	0	0.959	4.353
PAS_LAG_S	25,421	0.219	0.254	0	0.996	0.966
SIL_LAG_S	25,421	0.000141	0.00381	0	0.352	61.99
ACCSS_S	25,421	392.2	554.6	0.0113	3,084	1.902
NUTC_S	25,421	0.949	0.221	0	1	-4.068
OXGNC_S	25,421	0.119	0.324	0	1	2.355
NTRNC_S	25,421	0.799	0.401	0	1	-1.488
WORKC_S	25,421	0.209	0.407	0	1	1.429
INDGN_S	25,421	0.201	0.401	0	1	1.492
PRONAL_S	25,421	0.101	0.302	0	1	2.640
PRODPT_S	25,421	0.0671	0.250	0	1	3.459

The two versions of the model, with weak and strong forest governance, are statistically compared to assess whether there is a difference in the model parameters between the two forest governance regimes as follows. A likelihood ratio test is constructed based on 1) the log-likelihood function value for the two separately estimated models representing the unrestricted model wherein the coefficients from periods of weak and strong forest governance are allowed to differ and 2) a restricted model that constrains the coefficients between periods of weak and strong governance periods to be identical. The null hypothesis, thus, is that all model parameters are the same across the two regimes against an alternative hypothesis that at least one parameter differs.

The above test does not definitively determine whether the chief parameter of interest, access cost, has a differential impact across the two regimes, because it only focusses in determining what model explains better the variation in land use shares. In order to make a more focused determination about individual parameters, a paired bootstrapping procedure using STATA was applied to the unrestricted model. In this procedure, pairing refers to the joint distribution of the dependent and independent variables. This technique is used to obtain a description of the sampling properties of the empirical estimators $\widehat{\beta_j}$ by drawing the observed sample with replacement and re-computing the estimator on each new sample (Greene, 2012). The literature recommends at least 399 replications (Greene, 2012) and in this research 1,000 replications were used.

The initial output of the model is presented as the relative proportion ratio. Because this model is non-linear, the raw coefficients do not allow a direct interpretation for the effect of a marginal increase of the explanatory variables on the land use share. Consequently, elasticities of land shares with respect to the access cost were derived analytically and then estimated for all bootstrapped samples. Elasticities were computed at the mean values of the continuous explanatory variables and the most frequent value of the category variables for each access cost quintile. Subsequently, a t-test on the difference of means from the elasticities between the two forest regimes was implemented to assess statistical differences. The null that the response of access cost on land use shares is different between the two regimes is rejected whenever a zero value lies within the confidence interval of the difference on the means between the two regimes.

4.3 Clustering the results by access cost

Due to the inclusion of interaction terms, marginal effects in the above model are a function of the explanatory variables and vary based on the point where these are computed. Lagged land use shares and access cost are the continuous variables used in this model, and because the incentives for land transition are influenced by access cost, it becomes of interest to learn how the response changes based on the access cost level. However, the range of access cost is very wide (0.011 to 3084.294 person-hours per 10-ton load), and it would be impractical to analyze the response for every value on that range (Figure 4.1, Figure 4.2, and Figure 4.3). Instead, a segmentation technique is used to characterize the differential impact of access cost under different circumstances.

A Chi-squared automatic interaction detection (CHAID) algorithm available in STATA was used to segment the data into like pixels to gain improved insight about the role of infrastructure development across the landscape and development continuum. The algorithm uses the chi-square goodness of fit test to cluster the data according to categorical divisions of independent variables (van Diepen and Franses, 2006). For each explanatory variable, the test identifies any pair of categories for which there is no statistical difference on the response variable. Categories considered homogenous according to this metric are merged into a single category, and the categories that are deemed heterogenous are used to create clusters. There are some special rules in this algorithm depending on the type of variables. For instance, there is no restriction on the categories that can be merged for nominal (with no strict order) explanatory variables, which is the case of the dummy variables. However, for the ordinal variables, only those categories that are adjacent are allowed to be merged (Magidson and Vermunt, 2005).

The CHAID algorithm results in a tree structure defined by nodes where observations are segmented along with a categorical data definition, and nodes within the tree indicate splitting of the data into sub-group clusters of observations (pixels) with similar characteristics consistent with the chi-square goodness of fit test. An advantage of this approach is that one can easily determine why a specific observation falls into a cluster and what makes it similar to other observations in that cluster. Many other clustering algorithms are unable to provide this sort of valuable descriptive information.

The final nodes are called leaves and are the result of different combinations of explanatory variables. Provided the wide range of the continuous explanatory variables, the maximum amount of categories in which these variables could be fragmented was limited to 5; by default, these variables are split into quintiles, and then rearranged or merged based on the goodness of fit of each group with its neighbors; also, to preserve a relative large value of observations within each cluster, the minimum elements of each node was limited to 1,000.

The response vector has 5 types of land shares, but the CHAID analysis was limited to Forest, Pasture, and Crops. Silviculture and Other were not included in the analysis; the former because there are very few pixels that report values larger than zero for that category, and the latter because it is an aggregation of several land categories (urban areas, water bodies, mangrove non-vegetated areas, among others).

4.4 Results

The results presented here suggest that the data provide evidence that the response of land use to the explanatory variables differs depending on the two years 2003 and 2013, in which the latter period represents a stronger level of forest governance. The likelihood ratio test indicates that the restricted model (where coefficients are constant across the two years) is rejected in favor of the unrestricted model (loglikelihood ratio test pvalue < 0.000). This suggests that at least one of the estimated coefficients between the two governance regimes is statistically different and the variation in land use shares is explained better when the two forest governance periods are considered separately. The likelihood ratio statistic is 7950.24 while the Chi-square critical value with 14 degrees of freedom and a significance level of 1% is 29.14. The McFadden's pseudo-R^2 was used to measure of goodness of fit of the model. This statistic is the quantity one minus the log likelihood of the model, divided by the log likelihood of the null model, where the null model contains no parameters other than a single constant. Thus, this statistic provides a measure of the amount of variation in the data which is explained by the model relative to a naïve model which is analogous to R-squared in a standard regression context. The value obtained for this parameter was 0.41, and the literature reports values between 0.2 – 0.4 to be a benchmark of a good fit (Hemmert et al., 2016).

Out sample validation was carried out to assess the performance of the model, and the mean absolute error (MAE) and the root mean square error (RMSE) were calculated. For this validation, half of the observations were randomly taken out of the sample, the model was estimated and then those variables that were excluded from the model were used to assess the accuracy of the prediction on the model. Mean absolute errors across land shares ranged from 0.0004 for silviculture to 0.05, while the root mean square error ranged between 0.0069 for silviculture, and 0.0729. The lower the reported value on these indicators the better; however, the levels of the estimates of these variables need to be taken into account. The average level on the shares are 0.6676, 0.2029, 0.0361,0.0002, and 0.0932, for Forest, Pasture, Crops, Silviculture, and Other land use, thus the better adjustments on the prediction occurs for land shares on forest.

Table 4.4 Out sample validation MAE and RMSE

	FOR	PAS	CROP	SIL	OTH
MAE	0.0518	0.0505	0.0197	0.0004	0.0354
RMSE	0.0729	0.0755	0.0466	0.0069	0.0578

Due to the nonlinear form of the logistic function, the interpretation of the coefficients requires caution. First, the non-linearity prevents assuming the coefficients would represent marginal changes in the explanatory variables as in the case of linear regression models. Second, the effects from the explanatory variables are relative to one of the possible alternatives of the response variable – in this case the Forest land share. In other words, the coefficient values do not represent a direct effect over a response variable, but the effects on a ratio between the likelihood land use categories relative to the likelihood of the Forest land use.

However, the direction of the effect on the response variable can be inferred from the sign of the coefficients, and the results can be expressed as the relative proportion ratio of land uses with respect to Forest land use. Because the response variable relates to land area, the relative proportion ratio can be interpreted as how many units exist from any land use type per each unit of land on Forest (the scale of the unit is irrelevant, it could be acre, hectare, or another unit of area). Recall that due to the logistic form, all coefficients of the explanatory variables for the Forest land share are set to zero ($\beta_1 = 0$), and hence, that category of the response variable is used as a reference.

The STATA output reports the log of the relative proportion ratios, and the coefficient values were then transformed using the exponential function. The proportion of land use shares relative to Forest, and the multipliers that affect those proportions are presented in Table 4.5 and Table 4.6. Note that the values presented in these tables are obtained by exponentiating the fractional multinomial logit coefficients (f(β_j)=exp(β_j)), and because of the transformation, all the coefficients initially reported with a negative sign (denoting a negative effect) now are reported in the range (0-1), and all the initial positive values are reported (denoting a positive effect) are reported in the range (1,∞). For example, the parameter estimates of the lagged land use share in pasture (PAS_LAG_W) and the access cost (ACCSS_W) for the ratio Pasture:Forest (under the weak forest governance regime) were 5.7795 and -0.0018 (none of these are reported in this document), but when transformed these values become 323.60 and 0.9982 (reported in Table 4.5).

The first column of Table 4.5 and Table 4.6 contains the list of the explanatory variables used in the model. Common notation is used for the explanatory variables: "_W" denoted at the end of the variable stands for weak governance, while "_S" stands for strong governance; "PAS_", "CROP_", "SIL_", and "OTH_" indicates land shares on Pasture, Crops, Silviculture, and other land use; "_LAG" specifies the variable is from a former period (lagged). The complete notation of explanatory variables for the land-use model is presented in (

Table 4.1)

Columns 2 to 4 in Table 4.5 and Table 4.6 report the coefficients of the explanatory variables that affect the proportions between all land use shares relative to the Forest share. From left to right these columns refer to land use shares on Pasture (PAS), Crops (CROP), Silviculture (SIL), and other land use (OTH).

The relative proportion ratios for Pasture:Forest, Crops:Forest, Silviculture:Forest, and Other:Forest are reported as the constant coefficients in Table 4.5 and Table 4.6. For instance, the ratio Pasture:Forest which is presented at the bottom row and second column, can be interpreted as there are on average 0.0975 hectares of Pasture per hectare of Forest. The same logic applies for the other land uses: 0.0129 ha of Crops, less than 10E-4 ha of Silviculture, and 0.0170 ha of other land use per each hectare on Forest (Table 4.5 and Table 4.6).   Conversely, if the inverse function (f(x)=1/x) is taken to the relative proportion ratios, these values could be read in terms of hectares of Forest relative to other the reminder land uses: 10.25 ha in Forest per each of Pasture, 77.60 ha in Forest per each ha on Crops, 46,101.46 ha on Forest per each ha on Silviculture, and 58.9 ha on Forest per each ha on other land-use type.

Table 4.5 Relative proportion ratio for land use types with respect to Forest: Weak Regime

	PAS	CROP	SIL	OTH
PAS_LAG_W	323.6058***	7.4405***	745.2547***	48.3360***
CROP_LAG_W	2.7710***	5695.8436***	2147.7542***	46.8423***
SIL_LAG_W	3511.9229***	456.1967**	3.6426E+15***	16.3960
OTH_LAG_W	11.5951***	27.1913***	0.5295	2493.6306***
ACCSS_W	0.9982***	0.9909***	1.0027***	0.9998***
NUTC_W	1.1870***	0.8805	0.0706**	1.0854**
OXGNC_W	1.0053	0.1716***	0.1033***	1.5376***
NTRNC_W	0.8531***	2.6291***	9.9629**	0.9409**
WORKC_W	1.1068***	0.1629***	0.0020***	0.8601***
INDGN_W	0.4932***	0.4963***	0.0008***	1.1666***
PRONAL_W	0.3924***	0.0225***	0.1324***	0.9942
PRODPT_W	1.0000	0.4624**	0.0754**	0.9665
PRONAL_WxACCSS_W	323.6058***	7.4405***	745.2547***	48.3360***

PRODPT_WxACCSS_W	2.7710***	5695.8436***	2147.7542***	46.8423***
_cons	0.0975***	0.0129***	0.0000***	0.0170***

i) Levels of significance: * ($p \leq 0.1$), **($p \leq 0.05$), and ***($p \leq 0.001$)

Table 4.6 Relative proportion ratio for land use types with respect to Forest: Strong Regime

	PAS	CROP	SIL	OTH
PAS_LAG_S	198.6227***	6.3961***	586.9567***	30.6791***
CROP_LAG_S	3.3566***	1470.5945***	1318.9431***	42.0891***
SIL_LAG_S	3.37E+04***	2.38E+04***	6.34E+13***	9573.0391***
OTH_LAG_S	12.5396***	9.1860***	1096.1836***	4651.2813***
ACCSS_S	0.9984***	0.9953***	1.0026***	0.9998***
NUTC_S	0.7842***	2.5413***	0.2769**	0.7947***
OXGNC_S	0.9774**	0.6940***	0.2360**	1.4161***
NTRNC_S	0.9915	1.1595**	4.3762***	0.9667
WORKC_S	1.1116***	0.1885***	0.0229***	0.8029***
INDGN_S	0.6757***	0.6361***	0.0016***	1.1473***
PRONAL_S	0.6276***	0.1512***	0.0114***	1.1351**
PRODPT_S	1.0391	0.7043	1.0034	0.8554**
PRONAL_SxACCSS_S	0.9999	0.9973**	1.0002	0.9991***
PRODPT_SxACCSS_S	0.9998**	0.9989	0.9493**	0.9998**
_cons	0.0975***	0.0129***	0.0000***	0.0170***

i) Levels of significance: * ($p \leq 0.1$), **($p \leq 0.05$), and ***($p \leq 0.001$)

In the previous paragraph, the role of the constant coefficient to represent the relative proportion ratios was described. All of the coefficients next to the explanatory variables that are reported above the constant in Table 4.5 and Table 4.6 indicate by how much the relative proportion ratios on Pasture, Crops, Silviculture, or Other land-use, relative to Forest (second to fifth columns) are multiplied when the explanatory variable increases by one unit, keeping all else constant. For example when access cost increases by one hour, the relative proportion ratio Pasture:Forest is multiplied by 0.9982 (Table 4.5) and 0.998 (Table 4.6) under the weak and strong forest governance regimes. As these multipliers are less than one, the area in Pasture is reduced relative to the area in Forest when access cost increases.

It is noteworthy to reiterate that land use change is generally sluggish. This can be seen in the statistical significance of the coefficients on own-use lags. That is, for predicting the Pasture use, the coefficient on lagged Pasture is much greater than the coefficient on any of the other lagged uses, with the exception of Silviculture. The large magnitude of the coefficients of Silviculture is explained because the observed land shares are very close to zero for most pixels. Note that as far as any land use share type approaches to one, that land use becomes predominant and other land use shares are negligible. In the weak regime, when the own land use share (Pasture, Crop, Silviculture, or other) approached one in the lagged period, the relative proportion ratios are multiplied by the following magnitudes: Pasture:Forest by 323, Crops:Forest by 5,695, Silviculture:Forest by 3.64E+15, and other by 2,493 (Table 4.5). The larger the magnitude for which the relative proportion ratio is multiplied, the more likely is for any land use to increase in area at the expense of Forest. Conversely, for the case of Pasture:Forest, the multiplier of this relative ratio is 116 times smaller when the previous land use was Crops rather than Pasture (198.6227/3.3566). The same logic applies for the ratio Crops:Forest, in which the multiplier of the ratio is 765 times smaller when previous land use was Pasture rather than Crops (Table 4.5).

Table 4.7 Relative proportion ratio for land use types with respect to Forest- A marginal reduction on access cost

	Land Use type							
	PAS		CROP		SIL		OTH	
ACCSS_W	1.0019	***	1.0092	***	0.9973	***	1.0002	***
PRONAL_WxACCSS_W	1.0001		0.9948	***	1.0032	***	1.0005	***
PRODPT_WxACCSS_W	1.0002	*	0.9979	*	1.0046	***	1.0002	**
ACCSS_S	1.0016	***	1.0047	***	0.9974	***	1.0002	***
PRONAL_SxACCSS_S	1.0001		1.0027	**	0.9998		1.0009	***
PRODPT_SxACCSS_S	1.0002	**	1.0011		1.0534	**	1.0002	**
_cons	0.0975	***	0.0129	***	0.0000	***	0.0170	***

The first hypothesis, that market access improvement through road infrastructure does not induce higher deforestation, is rejected at the 0.1% level of significance. This means that access cost to the closest market has a statistically significant effect on deforestation. A marginal increase in access cost (higher market access barriers) reduces all other land use shares relative to Forest. As in the case of Pasture:Forest a one-hour increase in access cost multiplies the proportion ratio Crops:Forest by 0.9982 (0.18% reduction) and 0.9984 (0.16% reduction) under the weak (Table 4.5) and strong (Table 4.6) forest governance regimes. The interpretation of how access cost affects the land use shares, however, requires further analysis because the discussion will be based on the marginal reduction of access cost instead of a marginal increase (Table 4.7).

Recall that access cost was estimated in Chapter 3. This variable indicates how many person hours are needed to transport a load of 10 tones departing from a pixel to the closest market. In linear models, a decrease or increase of one unit of the response variable would have the same marginal effect as the coefficient remains the same. Provided the linear representation of the log of the relative proportion ratio, it can be appreciated that any unit increase in the explanatory variables does not have the same magnitude as the unit decreased after the log coefficients are exponentiated; i.e. assume 3 to be the magnitude of the log coefficient of a particular variable z, any unit increase or decrease of the variable z would increase or decrease by the same magnitude as the log relative proportion ratio of a particular land use; however, when those magnitudes are exponentiated the effect on the relative proportion ratio is different depending on whether it is an increase or decrease of one unit of the response variable. Using the same magnitude of 3 in the log coefficient, the effect of a unit decrease in the variable z, would multiply the relative proportion ratio by 0.049 (exp(-3)) while a unit increase would multiply the relative proportion ratio by 20.085.

Thus, a similar analysis is needed for the access cost variable that requires the sign of the log-coefficient to be switched before applying the exponential. A decrease of one person hour in access cost multiplies the relative proportion ratio Pasture:Forest by 1.0019 (a 0.19% increase) and 1.0016 (a 0.16% increase) for the weak and strong forest governance regime. That multiplier might seem small, but changes in road infrastructure are likely to result in changes in access cost that are much larger than one hour. A one-hour drop of access cost increases the relative proportion ratio Crops:Forest by 0.91% and 0.47% percent for weak and strong forest governance, respectively. In the case of Silviculture, a reduction of 1 hour in access cost diminishes the relative proportion ratio Silviculture:Forest by 0.27% and 0.26%, for weak and strong forest governance regimes, respectively. Regarding the other land use types, a one-person-hour decrease in access cost increases the relative proportion ratio Other:Forest by 0.024% and 0.023%. For all cases, the weak forest governance program revealed a larger impact. The statistical significance of those differences will be discussed along with the analysis of the elasticities below.

Those areas in a protected status have a lower risk for Forest being converted into Pasture or Crops. Land protection status reduced the proportion ratio for all land shares relative to Forest, except for Other land type uses.

The status of protected areas with indigenous people showed a statistically significant effect (at 0.001 level of significance) on the relative proportion ratio of all land use share types relative to

Forest, resulting in an effective policy to reduce deforestation. Recall that the relative proportion ratios indicate how many hectares are in each of the land use types relative to Forest. In territories with indigenous land status, the ratio Pasture:Forest is reduced between 32.43% and 50.68%, the ratio Crops:Forest decreased between 36.4% and 50.4%, the ratio Silviculture:Forest is diminished by 99%, while the ratio Otherland:Forest increased between 14.7% and 16.7%. For all the previous cases, the larger change in magnitude occurred under the weak forest governance regime, indicating a larger impact than in the stronger forest governance regime.

Protected land status at the national level was statistically significant for all land shares except for the Other land use at a 5% level of significance. For those pixels under protected national status the relative proportion ratio of Pasture:Forest was reduced between 37.2% and 60.8%, the ratio Crops:Forest is diminished between 84.9% and 97.8%, the ratio Silviculture:Forest dropped between 86.8% and 98.9.2%, and the ratio Other:Forest increased by 0.6% and 13.5%. The larger change in magnitude of the proportions on Pasture and Crops was provided under the weak forest governance regime, indicating a larger impact of the protection status in this regime than in the strong forest governance one

Protected areas at departmental level showed a significant effect (at 0.05 level of significance) on all land shares except for Pasture under the weak forest governance regime. This protection status reduced the relative proportion ratios of Crops:Forest and Silviculture:Forest by 53.8% and 92.5% Silviculture:Forest. Protected areas at the departmental level did not present statistical significance under the strong forest governance regime.

Protected national areas have a significant interaction effect on access cost (at a 5% level of significance), the relative proportion ratio Crops:Forest is reduced by an additional 0.53% and 0.92% under weak and strong forest governance. In all cases, a larger magnitude under the weak program means that any change in the explanatory variables has a greater effect on the land use shares when compared to the strong governance regime.

The interactions between access cost and national protected areas on expected land shares for Forest, Pasture, and Crops under a Weak governance, are presented in Figure 4.1, Figure 4.2, and Figure 4.3.

Expected shares in Forest are expected to increase with respect to access cost. That is, the higher the access cost on a given location, the smaller the potential return of the land. Average marginal effects evaluated at different values of access cost resulted in higher estimates for Forest shares in those pixels reported as protected land areas. It is noteworthy to mention that the marginal effects of access cost on Forest land share are positive for the entire range of access cost values on National Protected areas; Conversely, it is not the case that when areas are not Nationally Protected, the marginal effects of access cost on Forest land share become negative for any access cost is above 1900 person-hours (Figure 4.1).

Regarding Pasture and Crops, their expected shares increased in those areas that do not hold a national protection status. When not Nationally protected, land shares on areas with high accessibility comprise on average around 22% Pasture and 4% Crops 4% (Figure 4.2); while when protected, the land shares are around 14% for Pasture and less than 0.5% for Crops (Figure 4.3). Subsequently, the marginal effects of access cost on land shares for both Pasture and Crops have a larger magnitude along the entire range of access cost.

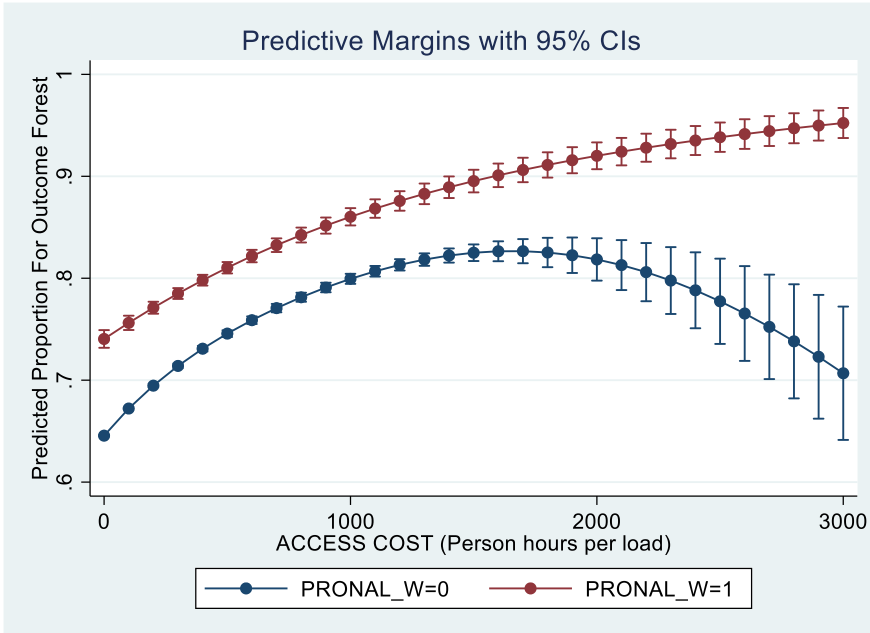


Figure 4.1. Predicted land shares of Forest with respect to access cost -Weak Regime *Protected vs Unprotected National Areas

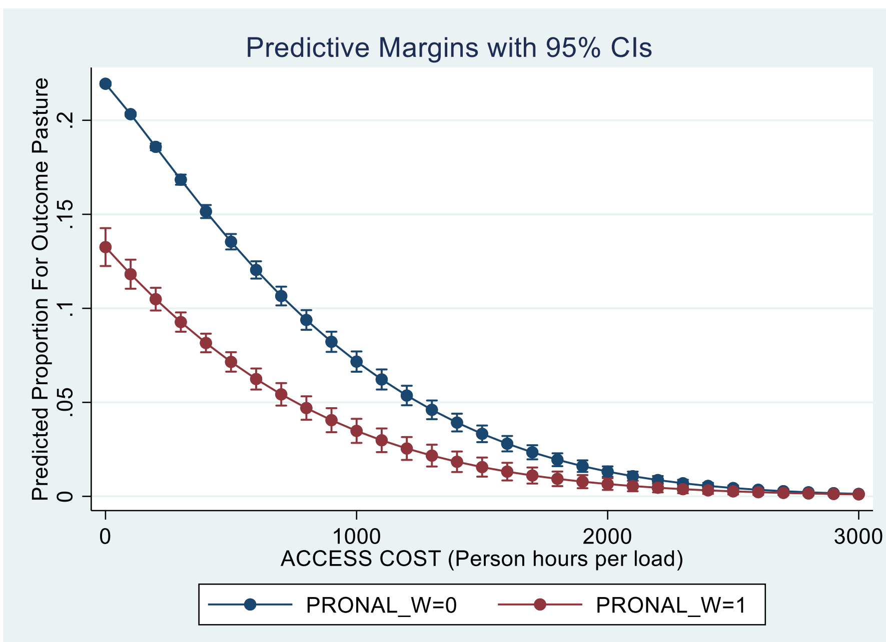


Figure 4.2. Predicted land shares of Pasture with respect to access cost -Weak Regime *Protected vs Unprotected National Areas

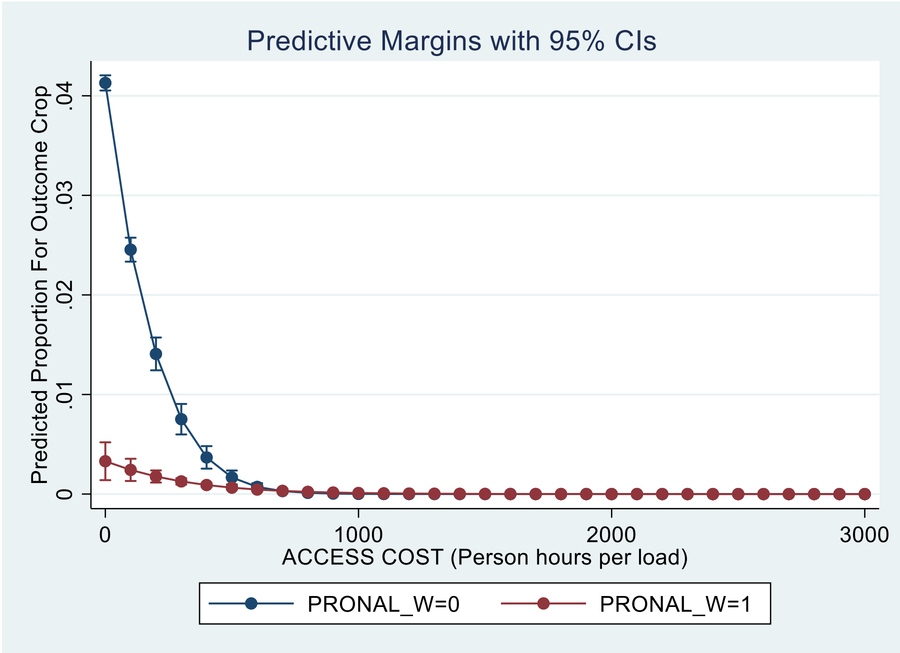


Figure 4.3. Predicted land shares of Crops with respect to access cost -Weak Regime *Protected vs Unprotected National Areas

In the studied area of Brazil, forested areas are mainly converted into pastures or subsistence crops, and then the pasture areas are subsequently converted into commercial crops. Between 2001 and 2017, land transition from Forest to Pasture in the Amazon basin accounted for 55.5% of total land conversion, while 24.9% of the conversion was from Pasture to Crops (Maciel et al., 2020). Cross lagged land use coefficients control for the dynamics in the transition of land from one use to another. Considering the difference in magnitude between the relative proportion ratio Pasture:Forest and Crop:Forest, the likelihood of areas that would transition from Pasture to Crops is lower compared to the transition from Crops to Pasture. That is explained by the difference in the magnitude of the multipliers of the relative proportion ratios when the cross lagged land uses Crops and Pasture. For instance, given the 9.75 hectares on pastures per every hundred on forest, that relative proportion ratio is multiplied by 277 (a magnitude 28 times larger than the ratio) when the previous land use happen to be in crops (Table 4.5); Conversely, there are 1.2 hectares of Pasture per every hundred hectares of Forest, and that relative proportion ratio is multiplied by 744 (a magnitude 576 times larger than the ratio) when the previous land use happen to be in Pasture. In addition, predicted shares in pastures are larger than 20% in areas with higher accessibility (Figure 4.2), while crops do not reach more than 5% in well-connected areas (Figure 4.3). Thus, the results of estimation appear to align with the observed patterns of land development in the region.

The segmentation obtained from the CHAID algorithm, showed access cost as one of the most important predictors that offers a different response across its range of values. CHAID analysis selected access cost quintiles in all the tree charts for Forest, Pasture, and Crops. In the case of Forest access cost resulted as the leaves of the tree, while in the case of Pasture and Crops, access cost was found as an intermediate node.

For Forest, each of the clusters observed at the leaves level contained 4,454 observations that represents the quintiles of the access cost variable. Thus, the first cluster contains the 20% of the observations that have the lower access cost value, while the fifth cluster contains the top 20% of observations with respect to their access cost value. For both Pasture and Crops, access cost appears as an intermediate node, and as in the case of Forest, each of those nodes contains 4,454 observations. Note that the lagged land use shares for Pasture and Crops are the leaves of the tree. This is consistent with the formulation of the land use model as past land use plays an important role in explaining the current land use.

The CHAID analysis revealed the relevance of access cost in the segregation of the data for estimating the land use shares. Given the relevance of that variable and the fact that none of the 5 categories that were pre-defined were merged, the access cost quintiles are considered in the next section to stratify the differences in the elasticities of reducing access cost through road infrastructure development among these groups on land shares.

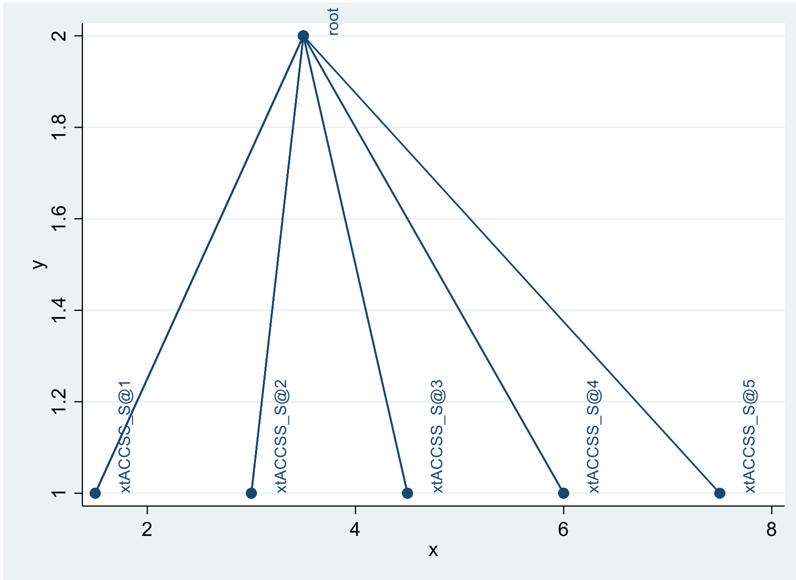


Figure 4.4. CHAID tree for Forest

Table 4.8. Observations CHAID for Forest

Group	1	2	3	4	5
Observations	4454	4454	4454	4454	4454

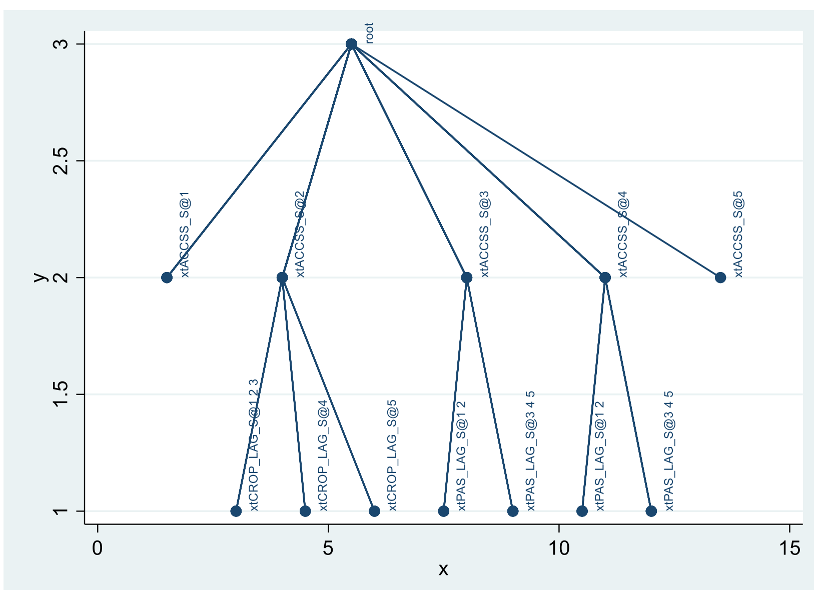


Figure 4.5. CHAID tree for Pasture

Table 4.9. Observations CHAID for Pasture

Group	1	2	3	4	5	6	7	8	9
Observations	4454	1664	1006	2925	4454	1278	1512	3448	1529

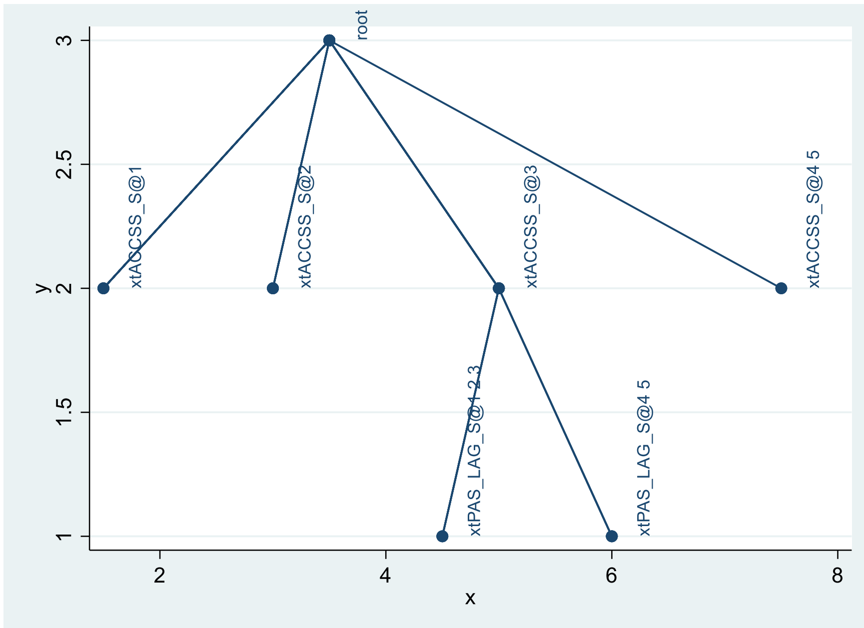


Figure 4.6. CHAID tree for Crop

Table 4.10. Observations CHAID for Crops

Group	1	2	3	4	5
Observations	4454	4454	2350	8908	2104

4.4.1 Elasticities of land use shares with respect to access cost

Recall that the observations were clustered with respect to the access cost quintiles in increasing order, cluster 1 is assigned to the observations of the lowest access cost group (1st quintile) so the cluster 5 is assigned to the highest access cost set (5th quintile).

Bootstrapped mean differences showed statistical significance between the two regimes on the elasticities of land shares with respect to access cost for all types of land shares. In each case, the hypothesis that the means of the elasticities are equal across regimes is rejected at all cluster levels and zero does not lie within the confidence intervals of the mean difference, nor in the inter-centile range (5%-95%) (Table 4.11 to Table 4.13).

Table 4.11. Mean differences of Forest land share elasticities with respect to access cost

Cluster	Mean differences (W-S)	Standard Error	Upper bound 95%	Lower bound 95%	Centile 5%	Centile 95%
1	0.00208	0.00001	0.00207	0.00210	0.00173	0.00245
2	0.01169	0.00004	0.01162	0.01176	0.00991	0.01356
3	0.02080	0.00007	0.02067	0.02093	0.01733	0.02418
4	0.00563	0.00004	0.00556	0.00570	0.00365	0.00748
5	0.00356	0.00006	0.00346	0.00367	0.00071	0.00656

*Elasticities reported for the observations clustered on the quintiles of access cost. The lower the cluster level, the smaller the values reported for access cost.
** W (Weak forest governance regime); **S (Strong forest governance regime)

Table 4.12. Mean differences of Pasture land share elasticities with respect to access cost

Cluster	Mean differences (W-S)	Standard Error	Upper bound 95%	Lower bound 95%	Centile 5%	Centile 95%
1	0.00104	0.00001	0.00103	0.00105	0.00071	0.00137
2	0.00320	0.00004	0.00312	0.00328	0.00108	0.00541
3	-0.01862	0.00021	-0.01902	-0.01822	-0.02924	-0.00773
4	-0.13109	0.00088	-0.13281	-0.12937	-0.17818	-0.08419
5	-0.39723	0.00266	-0.40245	-0.39200	-0.53947	-0.25387

*Elasticities reported for the observations clustered on the quintiles of access cost. The lower the cluster level, the smaller the values reported for access cost.
** W (Weak forest governance regime); **S (Strong forest governance regime)

Table 4.13. Mean differences of Crop land share elasticities with respect to access cost

Cluster	Mean differences (W-S)**	Standard Error	Upper bound 95%	Lower bound 95%	Centile 5%	Centile 95%
1	-0.01330	0.00005	-0.01340	-0.01320	-0.01593	-0.01054
2	-0.11363	0.00043	-0.11447	-0.11279	-0.13583	-0.09036
3	-0.56113	0.00208	-0.56520	-0.55705	-0.66915	-0.44929
4	-2.01281	0.00727	-2.02708	-1.99855	-2.38727	-1.62253
5	-5.91372	0.02130	-5.95551	-5.87193	-6.98196	-4.77089

*Elasticities reported for the observations clustered on the quintiles of access cost. The lower the cluster level, the smaller the values reported for access cost.
** W (Weak forest governance regime); **S (Strong forest governance regime)

The elasticity of the Forest land share with respect to access cost was positive. Any reduction in the access cost diminishes the Forest land share at the pixel. Large magnitudes of the elasticity arose under the weak forest governance regime, implying that the effects on land use are more substantial relative to the strong forest governance regime.

The largest impact of access on Forest occurs at the intermediate quantile of access cost, where a 1% reduction in access cost induce a drop of 0.082% of the land share in Forest. Elasticities shrink as access cost moves from the intermediate cluster to both of the extreme clusters. The response of the Forest land share reduction per 1% reduction in access cost drops to 0.006% and 0.027% on the lowest and highest access cost quintiles. These results are consistent with the established literature. Pfaff et al. (2018) argued that deforestation induced by road improvement would vary depending on the stage of development of the region. Little deforestation is expected in the short run in distant, undeveloped and isolated areas. Conversely, a larger deforestation effect is expected in those areas at an intermediate stage of development than in areas fully developed where the vast majority of land has already been has deforested.

The smaller effect is explained because, in those areas with lower access cost, most Forest land that has potential for other use has been already transitioned to other land uses, such as Pasture and Crops. In the lowest access cost quintile, a 1% change in access cost lead to a 0.0008% change in the Forest share under the strong regime, and a 0.0012% access cost in the weak regime. In the intermediate access cost quintile, a 1% change in access cost leads to a 0.057% and 0.081% change in the land Forest share, under the weak and strong regime, respectively. In the largest access cost quintile, a 1% rise in access cost increase by 0.029% and 0.033% the Forest land share, under the weak and strong regimes, respectively.

Even though the effects were fairly inelastic, with a 1% change in access cost resulting in less than 1% change in land use shares, the impact could be huge at the aggregate level because when a new road is constructed the access cost would typically be impacted by far more than 1%, and eventually even the most remote areas could move from its current cluster to a lower one.

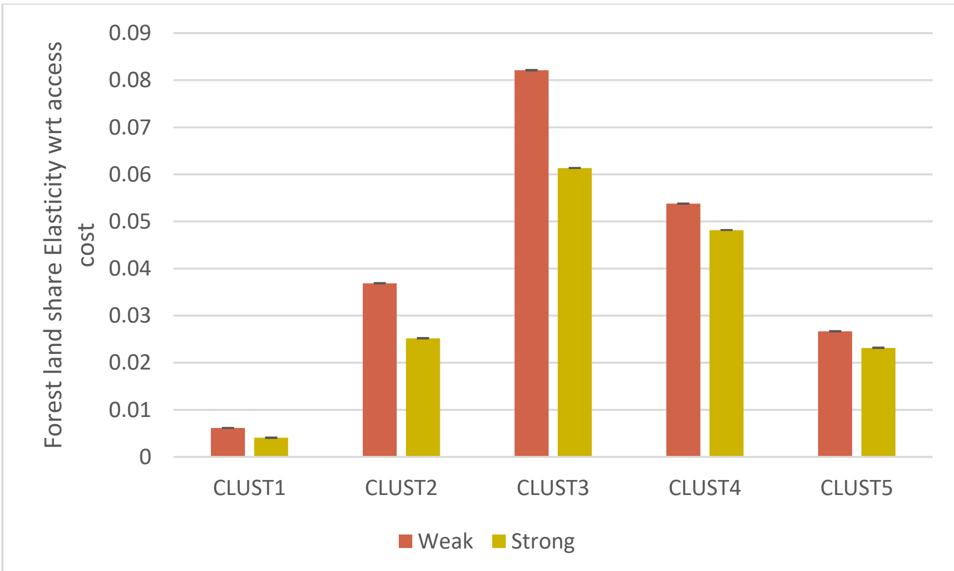


Figure 4.7. Forest land share elasticities with respect to access cost
*Under the two forest governance regimes (Weak and Strong) and five access cost clusters (Cluster 1 – the lowest access cost; Clusters 5 – the highest access cost quintile)

Elasticities for Pasture and Crop land shares with respect to access cost are negative indicating that any reduction in the access cost promotes the expansion of Pasture and Crops. For both land types, the magnitude of these elasticities increases from the lowest to the highest access cost clusters, implying that the impact of access cost on the land shares is larger in remote areas for Pasture and Crops.

Regarding Pasture land shares, these impacts are inelastic for most of the clusters except for the cluster with the largest access cost. At the group that represents the observations within the lowest

20% of access cost (the one with the lowest access cost), a 1% reduction of access cost increases the Pasture land shares by 0.0003% and 0.0013%, under the strong and weak forest governance program, respectively. In the intermediate cluster, a 1% change in access cost increases the Pasture land shares by 0.1442% and 0.1628%, for the strong and weak regimes, respectively. For the cluster with the highest access cost, a 1% decrease in access cost would induce a 2.065% and 2.463% change on Pasture land share, under the strong and weak forest governance program, respectively.

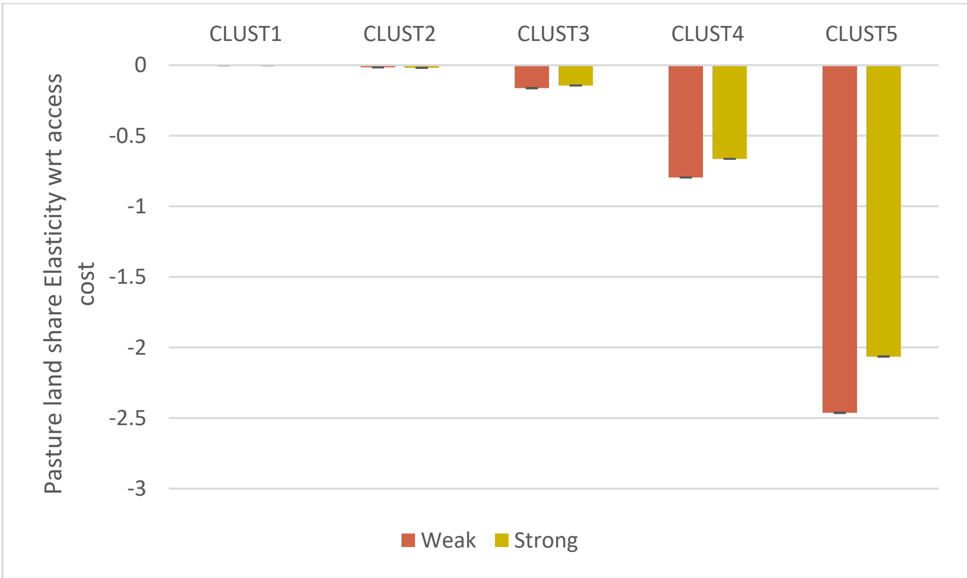


Figure 4.8. Pasture land share elasticities with respect to access cost
*Under the two forest governance regimes (Weak and Strong) and five access cost clusters (Cluster 1 – the lowest access cost; Clusters 5 – the highest access cost quintile)

Land shares in Crops are inelastic, except for the clusters 4 and 5 that focus on the 40% of the observations with the highest access cost. The weaker forest governance regime revealed a larger impact of access cost on land use for all clusters. For the first cluster, a 1% reduction in access cost induces a 0.0258% and 0.0125% increase of land shares in Crops. For the third cluster with the intermediate values for access cost, the change in the Crops share would be of 1.1250% and 0.5639%. The cluster with the largest access cost showed the largest impacts on land use shares, a 1% decrease in access cost generated a change of 12.24% and 6.33% in the land shares.

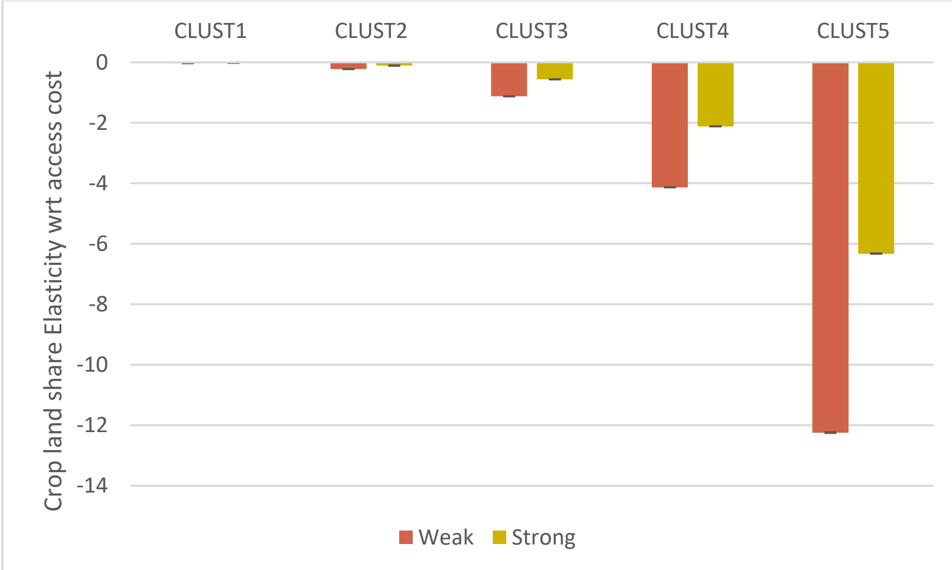


Figure 4.9. Crop land share elasticities with respect to access cost
*Under the two forest governance regimes (Weak and Strong) and five access cost clusters (Cluster 1 – the lowest access cost; Clusters 5 – the highest access cost quintile)

As mentioned, the analysis is not extended to Silviculture and Other land types. The analysis of those land shares has complexities and challenges that were not addressed in this research. For the case of land shares for Silviculture, very few observations had values greater than zero; while the Other land use category represents an heterogenous aggregation of all other land uses. Proceeding further in describing the results for these two land share categories makes their results unreliable.

4.5 Discussion

This chapter presented a land use model that allowed estimation of the effect of road infrastructure on land use change applied to the two states with the largest record on deforestation areas in Brazil. The model combined spatial data of different resolution under a fractional multinomial logit approach, and the specification tested revealed differences on the effect of access cost on land use shares between two different governance periods on changes of land use shares. To the best knowledge of the author, most of the literature has revealed that roads are one of the main drivers of deforestation, but none of them has addressed how that effect would change under alternative levels of forest governance, which is one of the main contributions of this chapter.

The results obtained in this chapter demonstrate the importance of forest governance in mitigating the effect of roads on deforestation. Statistical differences in the elasticities between the years of weak and strong forest governance revealed that the impact of roads on deforestation was reduced up to 25% for the year associated with strong governance. It is noteworthy to recall that the largest effects are expected in the frontier (which is assumed to be the third quintile); so actions to preserve, monitor, or control, should prioritize those regions. Even though the elasticity of land in forest with respect to access was found to be inelastic (i.e. less than a one percent change in forest share with respect to a one percent change in access), the changes in access associated with a change in infrastructure are likely to be substantially larger than one percent leading to potentially large deforestation impact.

The land use model implemented here allows prediction of changes in land use shares, and so, it can be used to assess how land use is affected when road infrastructure interventions take place. That feature is applied in the next chapter (Chapter 5). The impact of a shock to road infrastructure will be implemented to assess changes in land use and GHG emissions. Later in that chapter, a carbon tax/credit mechanism is implemented and operationalized under the variable access cost affecting the behavior of the landholders who will adapt their decisions on land use to those with lower emissions.

This model could easily be adapted to regions other than Pará and Mato Grosso; e.g. only in the Amazon more than 12 thousand kilometers of roads are expected to be constructed or updated across Brazil, Bolivia, Colombia, Ecuador and Peru (Vilela et al., 2020). That investment is estimated in USD$ 27 billion and could cause deforestation in 2.4 million hectares in the next 20 years.

Countries are expected to keep building infrastructure to promote economic activity; e.g. the Trans-Papua Highway in Indonesia with 4,000 km, the program “missing links” that plans to double the length the of Papua New Guinea road network (NYDF Assessment Partners, 2020), and the Belt Road initiative launched by China that is likely to connect at least 71 countries from Asia, Eastern Africa, Eastern Europe and the Middle East (“Belt and Road Initiative,” n.d.).

The potential of this model is not limited only to assessment of the effect of roads or any other infrastructure projects. Given that access cost is embedded in a von Thünen framework in which land use is influenced by the rents that potentially could be extracted from the land uses, any other element that affects profitability such as prices or yields could be assessed within this framework. Some limitations of this model rely on the definition of governance. As stated in Chapter 2, there are some initiatives to provide a framework to measure indicators of the level of forest governance such as the GFI framework from the World Resource Institute, and also Guides to Implement an Assessment from PROFOR and FAO. However, the interpretation of the indicators still is subjective and depends on the geopolitical context of each country. Besides, the construction of these indicators demands detailed and specialized data in some cases not available to the public. Further research on these topics, could allow implementation of other identification strategies such as the separation of the time trend of deforestation from the forest governance regime.

CHAPTER 5. ROAD INFRASTRUCTURE IMPROVEMENT AND CARBON TAX/CREDIT

Recall that in the previous chapter a model was implemented to estimate the impact of road infrastructure development on land use via a measure of access cost. The enhancement of the road infrastructure not only lead to deforestation, but also the transitions from one land use to another may lead to increased GHG emissions. The model is also useful in predicting changes in land use and associated environmental impacts.

In this chapter, carbon stocks and land use GHG emissions are estimated from a baseline scenario (year 2013) for Pará and Mato Grosso. Subsequently, a shock to the road infrastructure is implemented using the change in the road network between 2013 and 2018. A new land use configuration results from that shock, and carbon stocks and land use GHG emissions are re-estimated for that new scenario. Later, a carbon tax/credit policy instrument aimed at mitigating the increase of emissions is introduced in an effort to estimate the trade-off between emissions and the level of the tax/credit rate. The first section of this chapter describes the profit maximizing behavior that motivates land use change in response to the carbon tax; the second section describes the scenarios or stages used for the estimation of land use on each pixel; the third section presents estimates GHG emissions; the fourth section describes the implementation of the carbon tax/credit policy instrument; the fifth section offers a discussion of the results of the analysis and policy implications.

5.1 Profit maximizing behavior and land-use change

The following model is an abstraction of profit-maximizing behavior by land tenants. Conceptually, land is further spatially disaggregated below the pixel level into "parcels" for which land attributes are homogeneous and decisions regarding land use apply throughout the parcel. Thus, while land use is specialized on parcels, pixels that are made up of several parcels reflect heterogeneous land use. In this conceptual framework, profit maximization drives the choice of land use (j) at every parcel (p) in pixel (i). Gross revenues for the land use j on parcel p in pixel i are denoted by R_{jip}; costs for land use j on parcel p in pixel i, exclusive of land and transportation of inputs and outputs, are denoted by C_{jip}; transportation costs of inputs and outputs are expressed as $w * LD_{jip} * H_i + O_{jip}$, where w denotes the wage, LD_{jip} represents the loads of outputs from and inputs to production on land used in enterprise j on parcel p in pixel i, where one load equals 10 tons of output or input. H_i is the effort (in person-hours per ten-ton load) required to move one load out/in of the pixel to/from the closest market, and O_{jip} denotes the other costs of transport (depreciation, interest, repairs, taxes, and insurance). So, the land-use choice for each parcel p on pixel i is made according to the following discrete optimization problem:

$$j^* = argmax_j\left[R_{jip} - C_{jip} - w * LD_{jip} * H_i - O_{jip}\right]$$

Equation 5.1 Profit maximizing behavior at the parcel

Land use choice on parcel p is represented by LC_{jip} (a dummy variable that takes the value of one when parcel p is in use j on pixel i), and A_{ip} is the area of the parcel p at pixel i. The aggregation of parcel areas at the pixel level results in land shares, Sh_{ji}, by land-use j in pixel i as defined in the following equation:

$$Sh_{ji} = \frac{\sum_p A_{ip} * LC_{jip}}{\sum_p A_{ip}}$$

Equation 5.2 Land Shares

Land shares in a given pixel must sum to unity: $\sum_j Sh_{ji} = 1$

Changes in road infrastructure result in changes in H_i, which may have an impact on the parcel level choices LC_{jip}, and therefore on the shares Sh_{ji}. Those changes will induce changes in GHG emissions, which can potentially be offset by a carbon tax. When a Carbon tax is implemented, the model incorporates the total amount (in tons) of GHG emissions E_{jip} released from parcel p due to the choice of land-use type j, and a specific tax, τ, that is charged per every unit (ton) of CO2e released (Equation 5.3). Consequently, whenever the tax is positive and all else constant the tenant will choose land use so as to maximize after-tax profits.

$$j^* = argmax_j\left[R_{jip} - C_{jip} - w * LD_{jip} * H_i - O_{jip} - \tau * E_{jip}\right]$$

Equation 5.3 Profit maximizing behavior and carbon tax

If the variations in R_{jip}, C_{jip}, LD_{jip}, O_{jip} and E_{jip} motivate different choices across different parcels. The shares Sh_{ji}, represent the area weighted sums of land use across parcels within the pixel. To express the associated net revenue at the pixel level, we abstract from the variations in R_{jip}, C_{jip}, LD_{jip}, O_{jip} and E_{jip} across parcels to obtain the following expression for net revenue (Equation 4.2):

$$NR_i = \sum_j \left[R_{ji} - C_{ji} - w * LD_{ji} * H_i - O_{ji} - \tau * E_{ji}\right] Sh_{ji}$$

$$= \sum_j R_{ji}Sh_{ji} - \sum_j C_{ji}Sh_{ji} - \sum_j wLD_{ji}Sh_{ji}H_i - \sum_j O_{ji}Sh_{ji} - \sum_j \tau * E_{ji}Sh_{ji}$$

$$= \sum_j R_{ji}Sh_{ji} - \sum_j C_{ji}Sh_{ji} - H_i \sum_j wLD_{ji}Sh_{ji} - \sum_j \tau E_{ji}Sh_{ji} - \sum_j O_{ji}Sh_{ji}$$

$$= \sum_j R_{ji}Sh_{ji} - \sum_j C_{ji}Sh_{ji} - \sum_j wLD_{ji}Sh_{ji}\left[H_i + \frac{\tau}{w}\frac{\sum_j E_{ji}Sh_{ji}}{\sum_j LD_{ji}Sh_{ji}}\right] - \sum_j O_{ji}Sh_{ji}$$

Equation 5.4 Net revenue, effort, and carbon tax

Consequently, with a positive tax ($\tau > 0$), the access cost at the i-th pixel, H_i, is increased by $(\tau/w)\left[(\sum_j E_{ji}Sh_{ji})/(\sum_j LD_{ji}Sh_{ji})\right]$ as a result of the carbon emissions tax. Note that the units of this additional term are in $(person\ hours)/load,$ [4] which is the same as the units of H_i. In other words, the tax may be converted to an equivalent change in access cost. In effect, the tax is represented in terms of extra effort (cost) in the sense that it is more expensive to ship to and from a market when the cost of emissions is added. This outcome is useful because it allows the impact of the carbon tax on land use to be integrated directly into simulations using the estimated land-use model from Chapter 3. Subsequently, the estimated impact of alternative tax levels on greenhouse gas emissions is easily derived.

[4] $[(dollars\ per\ ton\ CO2e) * (tons\ CO2e)]\ /\ [(dollars\ per\ person\ hour) * (loads)] = (person\ hours)/load$

The model presented above is a conceptualization that motivates the use of the fractional land use model described in Chapter 3. It is noteworthy to mention that heterogeneity across parcels is captured by the fractions within the pixels.

5.2 Access cost scenarios and land use shares

As stated in Chapter 4, access cost derived from road infrastructure has a statistically significant effect on land-use shares. In the current Chapter, a motivation on how and why access cost affects the land use choices at the parcel has been provided under a profit maximizing framework, consistent with von Thünen. Since any change in road infrastructure is likely to affect the land-use configuration from a given period, in this chapter a shock to road infrastructure is implemented with application to Pará and Mato Grosso to address the effect of road infrastructure improvement on land-use change, the subsequent change in emissions, and to assess the role of a carbon tax/credit to mitigate those increased emissions.

The assessment is performed in three model versions that later will be motivate the designation of scenarios. The first, a base line year is selected (2013 was chosen deliberately because it was used to estimate the effects of road infrastructure in the previous chapter), the land use model from Chapter 4 is used to predict land use shares, and from that land use configuration carbon stocks and GHG land-use emissions are estimated. The second, a road infrastructure shock is implemented by simulating the enhancement of the road network from the baseline year to a future year (the 2018), the land use model from Chapter 4 is used to predict the land-use configuration derived from the enhanced road network and the subsequent carbon stocks and land-use GHG emissions are re-estimated. The third, a carbon tax/credit instrument is implemented to mitigate the increased GHG emissions that resulted from the shock. Consequently, three scenarios are analyzed to assess how infrastructure changes alter the land use configuration. These scenarios are denoted by the following two letter scheme: (1) Baseline - BL, (2) After road change shock - AS, and (3) after road change shock and tax – AT, and are described as follows:

1) Baseline – BL: The BL scenario represents the land share configuration under a "base" road infrastructure network. The road network data from 2013 is used to build this scenario. By that year, there were 2,139 and 3,700 kilometers in paved roads in Pará and Mato

Grosso. Land use is projected using the model to obtain baseline land use shares, carbon stocks and GHG emissions due to land use.

2) After the infrastructure shock (road network improvement) – AS: The AS scenario projects the effect of a shock of road infrastructure on the land use and GHG emissions, which are driven by the reduction in access cost at the pixel. Access cost is adjusted by replacing the road network data from the BL scenario with that of 2018. By 2018 the paved road network had expanded to 2,723 and 4,018 kilometers in Pará and Mato Grosso. Also, the entire road network along these two states expanded by 112 km between 2013 and 2018.
3) After infrastructure shock and tax/credit (road network improvement and tax/credit is implemented) – AT: The AT scenario implements a mitigation policy instrument to project how different tax levels of the tax (τ) impact the level of GHG emissions associated with the infrastructure shock, and eventually, what would be the tax that would reduce the level of GHG emissions from AS to that of the BL. A tax/credit policy is applied at every pixel by adjusting the access cost variable consistent with the bracketed term in equation V-4 above. A per-ton of CO2 tax/credit is charged per unit of carbon released/absorbed after the shock; so the larger the level of GHG emissions released from the shock to road infrastructure, the larger the tax required to offset it, and hence the larger the revenue collected, at the pixel. Note that to make the policy practical to implement, the tax per ton of CO2e emitted is applied uniformly across all pixels rather than a pixel-specific tax.

All three scenarios are created by using the coefficients estimated for the year 2013 in the fractional multinomial logit model described in Chapter 4. This implies that the form and parameters (β_j) of the function used for the estimation do not change with the scenario. When the shock to access cost is implemented, the impact of access cost on land-use remains the same but what changes is the effort required from every pixel to reach the market, and that drives a new land use configuration. Recall that this model allows the estimation of the shares of land cover at the pixel level based on the data from predictive variables on past land use, soil characteristics, land protection status, and access cost to reach the closest market. Land shares represent the estimated proportion that each land type holds within a pixel under each scenario q (Equation 5.5).

$$\widehat{Sh_{i,j,q}} = \frac{e^{\left(X'_{i,q}\beta_j\right)}}{1+\sum_{j=2}^{5} e^{\left(X'_{i,q}\beta_j\right)}}\ ; \quad j=1,...,5 \quad \text{where } \beta_1 = 0 \text{ for identification purposes}$$

Equation 5.5 for Land Shares estimates

where i denotes pixel (1,…22,270); *j* denotes land type (forest, pasture, crop, silviculture, other); (q) denotes scenario (1 BL, 2 AS, and 3 AT); and $Sh_{i,j,q}$ denotes share of land use type *j* on pixel *i* – for scenario q.

As shown in Chapter 4 the fractional multinomial logit model reveals statistically significant effects of access cost on the land type shares. A reduction of access cost increases, on average, the share for pastures, crops, and other land types at the expense of forest and silviculture. Because GHG emissions depend on the type of land cover, any change in the land use shares also affects the emissions. Two types of emissions were considered for this analysis: those from land cover/use change and those from ongoing land use.

5.3 GHG emission estimation

Emissions from land conversion (called "stock emissions" for simplicity in this research) result from the difference in carbon stocks between any two scenarios. These changes reflect the inherent amount of carbon stored in the soil and any carbon in the biomass associated with the land use. Both of these quantities vary depending upon the chosen land use. Carbon stocks are computed in accordance with the guidance of Intergovernmental Panel on Climate Change -IPCC. The IPCC is the body of the United Nations that provides policy makers with assessments of the current state of knowledge about climate change. CO2e emissions are estimated through changes in Carbon stocks under the premise that changes in ecosystem Carbon stocks are mainly due to CO2e exchange between land surface and the atmosphere (Buendia et al., 2019).

This methodology allows estimation of the differences in carbon content from soil, biomass, and dead organic matter between two states of nature. Organic carbon in mineral soils is stored in the first 30 cm of depth. Biomass consists of above ground biomass and below ground biomass, where the first relates to all living vegetation above the soil and the second to all living roots below the soil. Dead organic matter accounts for deadwood and litter, the former consisting of all non-living wood in the surface larger than 10 cm in diameter, while in the latter the diameter is between 2mm and 10 cm (Buendia et al., 2019). In this research, five land use types are considered: forest, pasture, crops, silviculture, and other type of lands.

The carbon stocks estimation was made following a tier 1 approach (Buendia et al., 2019), in which default equations and default parameters are taken from the literature. Approaches focused on other tiers (tier 2 and tier 3) use additional data that reflect country specific factors, and process model systems that account for an inventory measurement system for carbon. The estimates of GHG emissions due to changes in the carbon stock as computed in this research reflect the changes in carbon stocks that are reported in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for tropical moist and tropical wet IPCC climate zones* (Buendia et al., 2019). Carbon stock parameters per hectare are presented in Table 5.1.

Table 5.1 Carbon Stock per unit of area

Land type	Carbon Stock -CS (CO_2 tons/pixel)
Forest	4,013,437
Pasture	761,175
Crops	692,580
Silviculture	1,321,325
Other	0

Source: adapted from Buendia et al., 2019

Emissions from land use (named “flow emissions” for simplicity in this research) are estimated using a representative commodity in the region for each land use type, based on what is reported in the literature regarding the CO2 emissions released per ton of output. Due to lack of data at the pixel level, heterogeneity across production technologies and crops within the same pixel are not addressed in this research.[5] Instead, data on emissions from soybeans (the major crop in both regions) is used to model those emissions from Crops, and data from cattle is used to model those emissions from land in Pastures.

Table 5.2 Flow Carbon Emissions per ton of output

Land type	GHG emissions (CO2 tons/unit)	Units of output	$LUEM_j$ (CO2 tons/pixel)
Forest	0	NA	0
Pasture	4.8[a]	Ton of Beef	2040
Crops	0.186[b]	Ton of Soybeans	5533
Silviculture	2.6[c]	Hectare-year	898
Other	NA	NA	NA

Sources: (a) (Cerri et al., 2016) (b) (Raucci et al., 2015) (c) (Markewitz, 2006)

There is also a temporal asymmetry in land use conversion and carbon release and sequestration. That is, deforestation can occur rather rapidly to other land uses, but reforestation tends to be a more protracted process. Thus, reforested areas would hinge on time delay in receiving benefits from carbon sequestration. It would likely take decades to receive a market return on reforestation (in the absence of carbon credits or other annual incentives). Farming generates annual returns, the present value of which exceeds the future payments from forest activities because the latter are discounted to reflect opportunity cost of money. Consequently, it is less likely that land use will move from cropping or pasture to forest than the other direction in the absence of incentives such as carbon credits/taxes or forest governance structures.

Despite the acknowledgement of the asymmetry between carbon release and carbon sequestration due to deforestation and reforestation, this model treats changes in carbon stocks and emissions in the same fashion. That is a weakness of the model and should be addressed in future work. The immediate loss of carbon stocks per hectare when land transitions from forest to pasture is 382

[5] Future research should address this by attempting to disaggregate pasture and crop uses by environmentally friendly and conventional approaches.

tons of CO2e in tropical regions (Buendia et al., 2019), while the annual carbon that is stored (above and below ground) in an hectare that has been reforested is estimated in 4-8 tons of CO2e per year (The Intergovernmental Panel on Climate Change - IPPC, n.d.). In other words if the annual rate of carbon sequestered is constant, it would take between 48 and 96 years to restore the levels of carbon of a forested area. The need to create mechanisms that ensure long-term land use and management changes is an issue that plagues all current carbon credit approaches. Creating enforcement mechanisms that ensure long-term carbon sequestration are vital to their ultimate success. In that sense, the current research can be viewed as taking a long-run (48 to 96 year) perspective under the assumption of successful enforcement of long-term contracts.

Difference in GHG emissions between scenarios

Shocks due to road infrastructure improvements are likely to alter land cover and emissions. As shown in the Equation 4.2, taxes affect net revenue from the parcel, and this section describes how tax revenue is calculated from the pixel and the role it has for reducing emissions at the aggregated region level. Land transition for every pixel is assumed to happen in equal portions across *n* years in the following approach. The annuities of emissions are treated as a uniform series of payments, and weights to the emissions from land use (ELU) are added to reflect the proportion of land that remains in the current (After Shock=1) and former (Baseline=0) scenario q. In the following equation CS denotes the carbon stock and the difference between the carbon stocks represents the stock emission, ELU denotes the flow emissions, D denotes the opportunity cost of an emitted ton of carbon, and G denotes the annual difference in emissions released between the scenarios AS and BL. The expression for the discounted sum of carbon emissions over the n-year period is:

$$GD = \left(\frac{1 - \frac{1}{(1+r)^n}}{r} \right) \frac{(CS_0 - CS_1)D}{n} + \sum_{t=1}^{n} \left[\left(\frac{t}{n} ELU_1 + \frac{n-t}{n} ELU_0 \right) - ELU_0 \right] \frac{D}{(1+r)^t}$$

Equation 5.6 Present worth of GHG emissions

D is factored out on both sides, adding an index *i* for the pixel, and expanding the terms that reflect heterogeneous land. Denoting land shares Sh_{jiq},for pixel i, land use *j*, and scenario q obtains the following expression for the weighted sum of emissions over time:

$$G_i = \left(\frac{1 - \frac{1}{(1+r)^n}}{r} \right) \frac{\left(\sum_j E1_j (Sh_{ji0} - Sh_{ji1} \right)}{n}$$

$$+ \sum_{t=1}^{n} \left[\sum_j E2_j \left(\frac{t}{n} Sh_{ji1} + \frac{n-t}{n} Sh_{ji0} \right) - Sh_{ji0} \right] \frac{1}{(1+r)^t}$$

Equation 5.7 Additional GHG emissions released after the shock

where $E1_j$ and $E2_j$ are coefficients indicating the carbon stocks and land emissions per unit of area (pixel) from land type *j*, respectively.

5.4 Access cost and tax collected at the pixel

The annualized revenue in dollars estimated at the pixel is denoted by PIX_TAXD_i, in Equation 5.8, where τ is the tax level.

$$PIX\_TAXD_i = \sum_j \frac{E1_j \left(Sh_{ji1} - Sh_{ji0} \right)}{n} * \tau$$

$$+ \sum_{t=1}^{n} \left[\sum_j E2_j \left(\left(\frac{t}{n} Sh_{ji1} + \frac{n-t}{n} Sh_{ji0} \right) - Sh_{ji0} \right) \right] \frac{1}{(1+r)^t} * \tau * \left[\frac{r}{1 - \frac{1}{(1+r)^n}} \right]$$

Equation 5.8 Tax calculated at the pixel

Note that $PIX\_TAXD_{i,AT}$ is equivalent to the following expression in the profit maximizing behavior modeled earlier: $PIX\_TAXD_{i,AT} = \tau \sum_j E_{ji} Sh_{ji}$.

Equation 4.2 showed that the tax collected at the pixel can be added to the effort required to transport one load from the pixel to the closest market to induce changes in the profit maximizing behavior. Note that tax payments in dollars at the pixel level ($PIX\_TAXD_{i,AT}$) can be divided by $w * \sum_j LD_{ji}Sh_{ji}$ to reflect the same units as the effort, which are person hours needed for one load to reach the closest market Table 5.5. Subsequently, when expressed in person hours the annualized revenue can be denoted as $PIX\_TAX_{i,AT}$ in Equation 5.9. Note that $PIX\_TAX_{i,AT}$ is positive (tax) if the aggregated emissions at the are greater than zero, and negative (credit) if the aggregated emissions at the pixel are less than zero.

$$PIX\_TAX_{i,AT} = \frac{1}{w}\frac{1}{\sum_j LD_{ji}Sh_{ji}} PIX\_TAXD_{i,AT} = \frac{\tau}{w}\frac{\sum_j E_{ji}Sh_{ji}}{\sum_j LD_{ji}Sh_{ji}}$$

Equation 5.9 Tax payment at the pixel (units of effort)

Recall that the tax is implemented to diminish the emissions that resulted from a shock to the road infrastructure as the access cost is reduced. In the model, the effort is represented by the variable access cost. The variable that represent access cost at the pixel *i* after the shock is denoted $ACCSS\_S_{i,AS}$; when the tax is implemented this variable is represented by $ACCSS\_S_{i,AT}$. As a result, whenever $ACCSS\_S_{i,AT} > ACCSS\_S_{i,AS}$, the incentives for transitioning from forests to pastures or crops are reduced under the AT scenario with respect to the AS scenario. The carbon tax calculated at the pixel level raises the access cost (effort) whenever the balance in net carbon stocks decreases, reducing profits from the pixel, which discourages a potential increase in the land shares of crops and pastures at the expense of forest, and potentially reduces emissions. Conversely, whenever the balance in net carbon emissions increase, land users at the pixel can be rewarded because $PIX\_TAX_{i\_AT}$ acts as a credit. A per unit tax level can be identified that offsets the aggregated GHG emissions across pixels that results from the transition from BL to AT, which implies that the difference in emissions should be close to zero.

Finally, it is noteworthy that the impact of the tax as a strategy for mitigating the infrastructure change should focus at the aggregated level. That is, from a national policy perspective, the important thing is the impact of infrastructure and land use on the global stock of atmospheric

GHG. Deforestation is avoided when transitioning from Forest to other uses (including agriculture) becomes more expensive due to land tenants having to pay for the CO2e emitted. In this approach the carbon tax can also act as a carbon credit on some pixels, and land can be converted to less emissions intensive uses; so agricultural areas that transition to Forest or Silviculture would be rewarded with an equivalent subsidy of τ per each ton of carbon that is sequestered. The net revenue collected for the entire region is: $Tax\ revenue = \sum_i PIX\_TAX_{D_i}$

5.5 Results

In this section a shock in access cost is implemented to simulate the effect of an improvement of road infrastructure on land use and GHG emissions. The Baseline scenario (BL) was created using the access cost data from 2013, and the shock is implemented as a new scenario After Shock (AS) is created updating the access cost to 2018 levels for every pixel in Pará and Mato Grosso.

Shocking access cost and its impact on land shares and GHG emissions

In Chapter 4, results where clustered by access cost quintiles to reveal the differences in responsiveness of land use. Recall that these clusters are denoted as C1, C2, …, and C5, and each contains the observations that belong to a common access cost quintile. Consequently, the clusters C1 and C5 are comprised by the 20% of the observations that have the lowest and largest access cost levels, respectively.

Average changes in access cost between the two scenarios BL and AS are presented in Table 5.3. The mean of access cost for the BL scenario ranged between 10 and 2,988 between clusters. Access cost levels for the AS scenario dropped from 7 to 1,789 within the same clusters with respect to the BL. Because the observations are clustered by access cost, the lower cluster the lower the mean value of access cost reported within the cluster. The same applies to the changes in access cost which the largest change in magnitude occurred at C5. This is not particularly true when percent changes are observed. C1 had actually the largest percent drop in access cost, indicating that the largest relative improvements occurred in the better connected areas, probably because of the economic activity of those regions. The following large relative improvement occurred at the most remote areas where access cost fell on average by 60%. This could be explained due to the interventions performed after 2013 in remote areas with road projects such as the BR163, and BR153, BR174, and PA275.

Table 5.3. Change in access cost due to an access cost shock

Cluster	Mean of Access Cost (Person hours per load)		Change in Person Hours (AS-BL)	Percent difference
	BL	AS		
C1	10	3	-7	-70%
C2	37	24	-13	-34%
C3	236	109	-128	-54%
C4	735	420	-315	-43%
C5	2,989	1,200	-1,789	-60%

The land use shares are reported in Table 5.4. Consistent with the von Thünen framework, the shares in Pastures and Crops are increased as access cost is reduced. The feasibility of these enterprises, is reduced in areas with high transportation costs. Thus, areas better connected to the markets due to infrastructure development have the largest shares in Crops and Pastures (C1), and the largest shares in forest are located in the most remote areas (Cluster C5). As a consequence of the change in access cost, there was a slight increase of land shares of Pastures and Crops in all clusters mainly at the expense of Forest and Silviculture. Recall, that by definition, the land use shares range between 0 and 1 and when aggregated at the pixel level must add to one. Differences in the land shares between the two scenarios are reported as percentages (see Table 5.4). Note that the differences in land use shares between scenarios at first sight might seem negligible, but even when the differences are no more than a fraction of a percent they represent huge changes in land area. For example, in the last 48 years Brazil has lost 19% of its forest[6], which is less than 0.4% per year (Butler, 2020).

[6] By 1970 the total surface in forest of Brazil covered approximately 4 million square kilometers (Butler, 2020)

Table 5.4. Land use shares for the two scenarios

	C1		C2		C3		C4		C5	
	BL	AS	BL	AS	BL	AS	BL	AS	BL	AS
SH_FOR	29.39%	29.38%	43.52%	43.39%	66.66%	66.03%	89.99%	89.61%	95.49%	95.18%
SH_PAS	41.83%	41.84%	36.00%	36.09%	22.68%	23.15%	5.23%	5.54%	1.10%	1.36%
SH_CROP	13.57%	13.58%	6.80%	6.86%	2.06%	2.26%	0.30%	0.36%	0.01%	0.02%
SH_SIL	0.09%	0.09%	0.04%	0.04%	0.02%	0.02%	0.01%	0.00%	0.02%	0.01%
SH_OTH	15.11%	15.11%	13.64%	13.62%	8.57%	8.54%	4.47%	4.48%	3.38%	3.43%

The reduction of the land shares in Forest derived from the shock of access cost ranged between 0.01 to 0.63 percentage points[7]. However, that decrease had a meaningful estimated impact on GHG. Consider that the total area of Pará and Mato Grosso is 2.15 million km^2 and thus a 0.01 percentage point change is equivalent to 21,500 hectares. The total estimated release of GHG emissions due to changes in access cost accounted for 244.28 million tons of CO2 equivalent, which including both stock and flow emissions over a period of 10 years. That amount is equivalent to the emissions of 5.3 million cars in the US, considering the average car emits 4.6 t CO2e per year (US EPA OAR, n.d.). The term Net Carbon Stocks is used to aggregate both type of emissions, which is equal to the total carbon stocks for a given period after deducting the flow emissions. Net carbon stocks for the two scenarios BL and AS are presented in Table 5.5, detailed by cluster.

7 The term percentage point refers to the magnitude of the land share and is used for clarity. For example, on average land share in forest represented the 95.49% of the area for those pixels contained at cluster C5 in the BL scenario; after the shock, the land share in forest is reduced by 0.31 percent points to 95.18% (which is different to say that the forest land share was reduced by 0.31%)

Table 5.5. Net increase in emissions due to change in net carbon stocks

Cluster	Net_Carbon_Stocks (Million ton CO2e)		Net increase in emissions (-1)(AS-BL) (Million ton CO2e)
	BL	AS	
C1	8,018.6	8,016.7	1.86
C2	10,458.6	10,437.9	20.73
C3	14,527.5	14,423.0	104.56
C4	18,569.1	18,505.4	63.70
C5	19,527.5	19,474.1	53.43

The largest release of GHG emissions happened at Cluster 3 with 104.56 million ton of CO2 equivalent, followed by the clusters C4, C5. Cluster 3 is thought to be the start of the agricultural frontier as forest areas still represent the largest share among other uses, and access to the markets makes it challenging to pursue agricultural activities. The least effect on GHG emissions happened in the two lower clusters, where the area in agriculture has already been well-established and proximity to markets is driving the result that those areas remain in agriculture.

Carbon tax/credit implementation

In this research a carbon tax/credit mechanism is proposed to mitigate both stock and flow GHG emissions. That mechanism consists of charging a tax per every ton of carbon that is released or captured. This research does not address the mechanism by which such a tax is collected or who bears the incidence of the tax. However, it provides useful information regarding the magnitude of the carbon tax/credit required to mitigate the emissions generated from the land use transition. This research addresses specifically those emissions generated from a shock to road infrastructure, but the mechanism has the flexibility of addressing other drivers of land use change, other than roads.

This mechanism would allow both charges or rewards per unit of area depending on the net change in emissions. It differs from the existing Rural Land Tax, which acts as an incentive for ranchers to deforest land because deductions are received based on a “degree of land utilization” (de Almeida and Uhl, 1995). The degree of land utilization is a ratio of current land used in agriculture with respect to the available land for agriculture of the farm. For example, assume two farmers have the same size of land endowment and produce the same quantity of a given commodity. However, suppose that one of them uses all her available land in agriculture while the other, who has higher yields per unit of area, decides not to crop her entire land. In such a scenario, the degree of utilization for the less productive case will be larger yielding that tenant more tax deductions.

The tax/credit mechanism proposed in this research intends to reduce the emissions to the pre-existing level of the Base line scenario to mitigate any shock that drives land-use change. In this context, the improvement in road infrastructure as access cost (Table 5.3) drives the change in land use, and so the change in GHG emissions Table 5.5. The level of emissions that are generated (captured) from that land use change are is (or credited) with the per ton Carbon tax/credit, and those charges are implemented at the pixel level resulting in altered decisions of the land user (Equation 5.3). Those taxes/credits are expressed in the same units as access cost (person hours per a 10 ton load; see Equation 5.9) and implemented into the profit maximizing behavior by increasing (decreasing) the value of the variable access cost in the case of a carbon release (capture). The equivalence between the carbon tax/credit level and the value of tax revenue collected at the pixel reported in the same units of access cost is presented for each cluster in Figure 5.1 . These values are added to those access cost levels reported in Table 5.3 for the AS scenario.

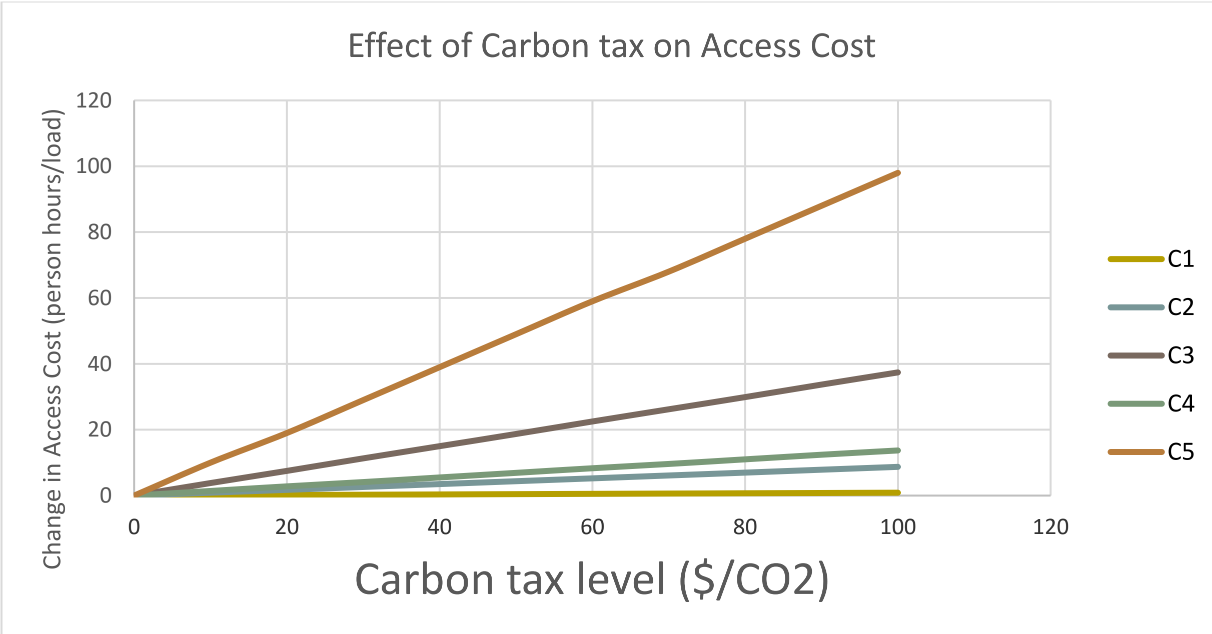


Figure 5.1 Carbon tax/credit level and the impact in access cost

As the carbon tax/credit mechanism is implemented, land users adapt their decisions to maximize net revenue for their parcels. That is reflected in land adjustments that prevent deforestation and incentivize land conversion from a high-carbon emissions land-use to a lower-carbon emission land-use. Subsequently, the effect of those decisions is reflected in the reduction of GHG emissions. The effect of the carbon tax/credit mechanism on GHG emissions for every cluster is presented in Figure 5.2. The vertical axis accounts for the additional GHG emissions released due to the shock of access cost at different carbon tax/credit levels are implemented. For instance, with a carbon tax/credit value of zero the intercept of all the abatement curves is equal to the level of GHG emissions reported in Table 5.5. Because the largest emissions release occurs on the frontier (Cluster C3) the largest effect of the tax on the reduction of GHG emissions occurs within that cluster which is consequent with the slope of the abatement curve.

The lowest increase in access cost associated carbon tax happens at the cluster C1 (Figure 5.1). That cluster has the lowest rate of conversion from forest to other land uses, and is comprised by the pixels with the lowest access cost or better connected to the markets. On average, emissions in cluster C1 can be abated at a carbon level of $36/ton CO2e. It follows that the tax level (per ton of CO2e) required to abate the aggregated emissions is $42, $56, and $86 for the clusters C2, C3, and

C5. Surprisingly, cluster C4 did not follow that pattern. Even with a tax of $100/ton of CO_2e, it would not be possible for that cluster to return the emissions to the pre-existing levels from the BL scenario.

Recall that the model allows for both taxes and credits to be associated with changes in GHG emissions depending upon their signs. Thus, it is expected that some locations will have larger net carbon stocks, while others will reduce their net carbon stocks levels. The carbon tax/credit level that would induce an aggregate net zero balance on GHG emissions after the shock on road infrastructure is $82/ton CO_2. That value seems high relative to other alternatives to reduce GHG emissions, but within the range of prices required to prevent a rise in temperatures above 2°C. The World Bank reports that around 7,000 out of 8,300 $MtCO_2e$ are charged at prices less than $20/$tCO_2e$ (The World Bank, 2020. At those price levels a carbon tax/credit would offset up to 24% of the total emissions from the access cost shock.

Note, however, that by 2017 only 15% of worldwide emissions were offset by diverse carbon pricing mechanisms, which implies that the discussion on carbon pricing and regulation needs to keep progressing. The World Bank also reports that to achieve the goals of the Paris Agreement carbon prices should range between US$40–80/$tCO_2$ by 2020 and US$50–100/$tCO_2$ by 2030 (The World Bank, 2020) indicating that the estimate of $82/$tCO_2e$ from this analysis is consistent with the literature.

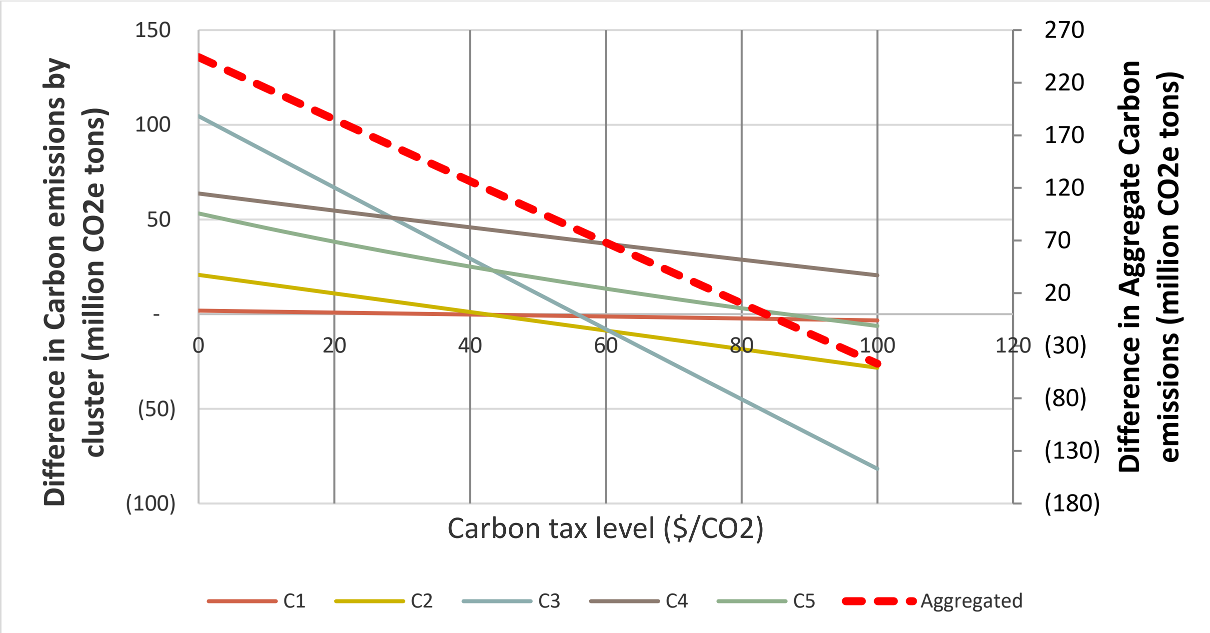


Figure 5.2 Carbon tax/credit level and its incidence in GHG emissions

5.6 Discussion

Carbon pricing is gaining relevance worldwide, and several countries are considering or have implemented alternatives on carbon pricing. Recently, there have been relevant price changes for carbon taxes in several countries. For instance, in 2020 carbon taxes increased from US$14/tCO2e to US$21/tCO2e in Canada, from US$7/tCO2e to US$28/tCO2e in Ireland, and from US$49/tCO2e to US$53/tCO2e in Norway (The World Bank, 2020).The private sector has been implementing in their decision making internal carbon prices, as a measure to prepare to an eventual scenario in which governments put a price on carbon (Stiglitz et al., 2017). That is the case of Microsoft that recently have contracted to buy 100,000 tons of carbon credits from Land O' Lakes at $20/tCO2e(Plume, n.d.). This research contributes to that discussion with an application to the Pará and Mato Grosso regions of Brazil. In the case of Brazil, discussions about carbon pricing are making progress, but no carbon pricing policy has been scheduled or implemented by any regulatory framework to date (The World Bank, 2020).

The results from this chapter are relevant as they inform to policy makers, scholars, land owners, farmers, and the public in general, about carbon policy needed to abate emissions derived from road improvement. The results also contribute to the broader carbon policy discussions related to protecting highly-forested areas such as Brazil upon which the entire world depends. The tax/credit mechanism implemented in the land use model was designed to estimate the impact of different level of carbon prices on the abatement of the emissions arising from improvement of road infrastructure. Emissions were of the order of 244.28 MtCO2e over a time span of 10 years. This amount is equivalent to approximately one tenth of the total emissions of any of the two states Pará and Mato Grosso. The results indicate $82/ton of CO2 equivalent as the tax level needed to abate the total of the additional GHG emissions derived from land use change due to a shock to road infrastructure. The analysis at the cluster level indicated that even though the shock to access cost introduced largest emissions impacts in the middle access cost quintile, abatement is much faster in that segment of the pixel population, which is consistent with the elasticities presented in the previous chapter. It is important to recognize that a total abatement of emissions is very unlikely, but regional authorities could target specific targets, and this model allows to inform policy makers on the carbon tax/credit required to attain those targets.

The understanding of carbon prices and the implementation of mechanisms that account them to reduce emissions are relevant to combat climate change. In this research, a contribution is made on this matter with the discussion of a carbon a land use model that implements a carbon tax/credit instrument understand how land users may respond to different tax/carbon levels. According to the High Level Commission on Carbon Prices, one of the changes in the global economy to achieve zero net emissions and limit global warming to less than 2°C increase is the optimization of the landscapes, by preserving and improving carbon sinks (e.g. management of forest, soil and changes in agricultural practices) (Stiglitz et al., 2017). Carbon pricing provides incentives for low-cost abatement options, because it creates opportunities to increase profitability as GHG emissions are abated or to reduce expenses by reducing emissions. It also encourages producers to decrease carbon intensity in the energy and manufacturing sectors, and incentivizes consumers to transition to less carbon-intensive goods.

This research contributes to the discussion regarding carbon pricing as a strategy for preserving and improving carbon sinks. Particularly, this is addressed by assessing a carbon tax/credit instrument and its effects on land use change and the offset of stocks and flow emissions. This is modeled under a profit maximizing framework in which the decisions of the land tenant regarding land use are influenced by the rents derived from potential uses that could be undertaken in a plot. Consistent with von Thünen, those rents are influenced by access cost, and when the tax/credit is implemented, it also incents the decisions on land use, favoring those activities with low carbon emissions.

Revenue from the carbon tax can be used to promote inclusive growth in different ways such as the return of revenue to households, support of the most vulnerable of the population, support of those who lose in the transition to a greener economy, the investment in low carbon initiatives, and the promotion of technological change (Stiglitz et al., 2017).

This research does not address how the tax/credit mechanism should be implemented. Rather, it provides a framework that describes how a carbon tax/credit mechanism affects the land choices at the pixel level. However, the mechanism allows taxation on those pixels where net carbon stocks are reduced, and tax credits for those pixels where net carbon stocks rise. Naturally, with the implementation of the carbon tax/credit program there will be winners and losers, and this needs to be addressed in future research. One alternative could be the redistribution of tax revenue based on environmental performance. That is the case of a program called Tax on the circulation of goods and transportation and communication services (ICMS-E), a mechanism in which the revenue arising from that taxation is allocated to municipalities based on their performance on environmental indicators. The principle is that municipalities with areas under conservation should be compensated for their loss of revenue, and the revenue collected from the ICMS-E is redistributed to those areas. conservation units (CUD Areas with low productivity lands have incentives to increase their land in conservation, such as Paraná and Minas Gerais (May et al., 2012). Environmental performance is measured by indexes such as the Biodiversity Conservation Coefficient, which represents the proportion of area under conservation in the municipality over the total land of the municipality.

It is noteworthy that the Forest Code currently regulates the ability of farmers in Brazil to clear new areas for agriculture production, and imposing a carbon tax/credit scheme is likely to affect farmers' competitiveness in international or local markets where foreign commodities are not similarly regulated. In this context it is relevant to understand whether the carbon tax/credit scheme is compatible with the existing Forest code, and what would be the role of the carbon tax on the existing regulation as there are already instruments that allow farmers to compensate for the deficit of areas under the Legal Reserve, such as the environmental reserve quotas (CRA) and reforestation programs. Another issue that needs to be addressed in future work is a determination of whether the tax/credit mechanism would add an extra burden to the Brazilian farmers.

The Forest code requires all private properties in the Amazon biome to have at least 80% of their total land area in forest or native vegetation. Any carbon tax/credit mechanism that is implemented should be aligned with this regulation, so that even when deforestation is expected after the enhancement of the road infrastructure and a carbon tax/credit is implemented to incent forest conservation or even reforestation (or other less emission intensive uses) in other areas, the amount of legal deforested areas derived from the road improvement must be within the limit of the legal reserves of the private properties. Thus, a carbon tax/credit scheme would not alter the allowances on legal reserves, but farmers might be facing a choice on whether to reduce the land in excess of their reserves.

One of the mechanisms that facilitates land user compliance with this regulation is the trade of CRAs. The CRAs are a tradeable mechanism that allows landowners to purchase forest certificates from other properties to offset the illegal deforestation that occurred before 2008 on their Legal Reserves (Soares-Filho et al., 2016). This mechanism allows land users who deforested beyond the limits of their Legal Reserve, to offset their pre-2008 deficits on deforested areas by trading CRAs that would compensate someone else that has excess legal reserves (Brito, 2017). Landowners that currently have areas in excess of their legal reserves already have the opportunity to register those areas as CRAs and receive compensation by selling these certificates on a CRA trading market; or could use the land in excess for developing any economic activity. Road improvement would make those economic activities more attractive; however, farmers would have fewer incentives for deforestation with a carbon tax/credit mechanism, because they would be charged a fee due to carbon emissions.

The carbon tax/credit mechanism is not likely to affect the competitiveness of farmers in current production areas because they do not have to bear the carbon tax costs associated with converting the land to crops or pastures. However, the tax/credit will impose an additional burden on those who decide to clear new areas after the implementation of a carbon tax/credit mechanism. In such a context, farmers could take advantage of their current areas in excess on legal reserves and receive credits from CRAs, also because the existing markets on forested lands are gaining attention.

It is noteworthy to mention that all areas deforested in excess from the legal reserves after 2008 will not be able to use CRAs to comply with the forest regulation; instead, land users must reforest their areas to comply with the regulation. Even though land users are not able to use the reforested areas to supply new CRAs, a carbon tax/credit mechanism could benefit them as they could receive credit for the increase in the carbon stocks on their property. That credit, however, should be less than the tax farmers would need to pay when areas are deforested, otherwise, there might be an incentive for deforestation and subsequent reforestation to gain carbon credits. Another complication that needs to be addressed in future research is potential the distribution of the tax revenue on those farmers who are currently complying with the forest regulation, to incent the adoption and maintenance of low carbon practices. In the event this is not addressed farmers may perceive as unfair the special treatment of those who historically have not complied with the forest code. Thus, funds from tax revenue need to be used also to compensate the farmers who have been complying with their legal reserve requirements and are engaged with the adoption of agricultural practices that allow for carbon sequestration

Another potentially fruitful avenue of future research would investigate the market for CRA's to determine how they respond to both infrastructure development and carbon taxes and credits. As has been demonstrated, infrastructure development generates differential impacts across space and likely created substantial gains from trade in CRA's as some farmers see the opportunity cost of land conversion rise while others may experience little or no impact. The current analysis does not impose the 80 percent reserve on land use and the land use model was estimated from data generated under the CRA trading policy. Thus, in the background, it should capture such trading opportunities under a carbon tax/credit scheme. That said, exploring this market and adding it to the model could generate some important fine tuning, especially with respect to land use and emission mitigation at the frontier where trading in CRA's should be at its liveliest.

CHAPTER 6. CONCLUDING REMARKS

This research discussed and presented evidence regarding the role of roads on deforestation and land use change, the relevance of forest governance in diminishing the impact of roads on deforestation, and assessed a mechanism to mitigate the additional GHG emissions derived from road infrastructure improvement which is a carbon tax/credit.

The first two chapters presented the motivation for this research and provided some context on the literature on roads and deforestation, forest governance, and carbon pricing. Road investments are likely to be used for governments to enhance economic development, especially in the remote areas. Roads benefit citizens and firms in different ways. People have better access to goods, services, and employment opportunities, while farms can reduce the transportation cost of their inputs and enhance the farm gate price of outputs. Other firms also benefit from roads because they are able to reach new markets easily and labor becomes more available. Despite those benefits, the improvement of a road network comes with negative externalities such as deforestation and the subsequent release of GHG emissions. Agriculture, forestry, and other land use sectors are responsiblefor about 23% of global GHG emissions. Road improvements are likely to increase GHG emissions because of a reduction on carbon stocks from land use change and the subsequent increase on flow emissions from agricultural and industrial activities. As transportation cost are reduced, the potential rents that can be extracted from a given plot change, which offers new opportunities to pursue new endeavors at that plot. A set of activities on forest governance that involves the private and public sector, as well as international organizations has been described as a mechanism to reduce the impact on deforestation. In addition, more than 190 countries have committed with National Determined Contributions to reduce their carbon emissions at the COP 21 Climate Change Conference in Paris. These commitments have the goal of limiting the increase in global average temperatures to less than 2°C, and preferably to limit the increase in temperatures to less than 1.5°C. Pricing carbon incents a more ecologically friendly consumption of goods and helps compensate projects aimed at sequestering carbon or to implement low carbon production practices, and the role of a carbon tax is also discussed as a mechanism to reduce the effects on emissions.

Chapter 3 described the estimation of the access cost variable, which is a representation of the effort required to reach the closest market in terms of time. This is important because changes in road infrastructure can have a direct, substantial impact on this level of effort for a given pixel. The access cost variable extracted the geo-referenced data of road infrastructure and translate it a spatial measure for every pixel. An innovation of this measure of accessibility is that it is represented in terms of effort rather than distance; units of access cost are expressed in person hours per load of 10 tons of output. Because access cost is related to an output level, costs associated with that output can be expressed in the same units as access cost and may alter the decisions on land use choice; i.e. carbon tax/credits per ton of output. Access cost can be represented graphically as heat maps to reveal how easy is to reach the markets from every pixel in the grid within a same period of time, or across different periods. In this research, most of the changes in the heat patterns across years were identified qualitatively at the middle quintile of access cost, which corresponds to the frontier.

Chapter 4 implemented a model to determine the effect of access cost derived from road infrastructure in land use shares. As access cost values ranged between 0.1 and 3.08 thousand person hours per load, the lower the value of access the better the connectivity to the markets. In the case of Para and Mato Grosso, Forest achieved land shares over 95% in remote areas while these shares drop to 65%-75% on the better connected areas. When access cost is reduced, shares on Pasture and Crops increase at the expense of diminishing the Forest share. Forest governance plays a relevant role in the reduction of deforestation from roads as its impact can be reduced up to 25% in the agricultural frontier.

The estimates of trade offs between carbon tax levels and emissions are a huge contributions to policy makers who are searching for ways to quantify the impacts of alterative policies. They must foster economic growth but want to do so responsibly. Armed with your graphs and information about how roads impact economic activity they can now make much more informed policy decisions.

Chapter 5 conceptualized a carbon tax/credit as a driver of the decisions on the land use choice, used the land model from the previous chapter to implement a shock to access cost, and evaluated the different levels of a carbon/tax to mitigate the additional GHG emissions that resulted from the shock. The shock generated additional GHG emissions of 244.28 MtCO2e, and a carbon tax level that would abate that total of emissions was estimated to be $82/tCO2e. However, the relevance of this model stands on the ability to link potential goals on GHG emissions reduction to the carbon tax/credit prices that would allow to attain that goal.

Regarding Pasture and Crops, their expected shares increased in those areas that do not hold a national protection status. When not Nationally protected, land shares on areas with high accessibility comprise on average around 22% Pasture and 4% Crops 4% (Figure 4.2); while when protected, the land shares are around 14% for Pasture and less than 0.5% for Crops (Figure 4.3)

Forest governance has a strong effect on reducing the impact of roads on deforestation and is likely politically more acceptable than the implementation of a carbon tax/credit mechanism. In this research the implementation of a carbon tax/credit scheme was discussed as an alternative to abate the additional emissions generated on the land use transition derived from road infrastructure. However, the consequences for farmers that are currently complying with the existing forest code regulation were not addressed, and further research should address those issues. So far, forest governance has proven to work in diminishing the impact of deforestation and efforts should be aligned to maintain a coalition across the private and public sector to keep enhancing forest governance. In this research it is revealed that most of the specific actions of forest governance need to target the frontier, as in these specific areas the largest effects on deforestation are expected, but also the mitigation strategies are more impactful.

This research embodies a variety of limitations and caveats of that will be described in the next paragraphs.

The scope of this research relies on an understanding the relationship between roads, deforestation, and mitigation strategies. The approach undertaken here is to estimate access cost based on estimates of impedances at the pixel level. These impedances were assigned based on the type of surface on the pixel. However, these speeds may be affected by weather, especially the unpaved roads during the rainy season. In the rainy season, trucks get stuck because of muddy conditions, and the time required for them to continue their journey varies case by case. An alternative used to adjust for this condition was to assume that no transit is possible in those roads during the rainy season, and compute an average of the travel speeds across months.

One of the main limitations of this study is the scarce data on unofficial roads. Because of their "illegal status" data on these roads are not collected by government agencies in Brazil. Including illegal roads is relevant as these roads are constructed to connect illegal logging from forest to distribution centers. This could be an area for further research. Part of this issue could be addressed by eliciting a road network from Satellite Images. There are techniques for an automated detection process that can be used; however, field work might be required to determine the quality of those roads. That task could be a complex task for emerging countries that count with limited data available on the road network over different years.

Another limitation of this study is that it only focuses on the road network. Further work could incorporate multi-modal transportation, particularly the railroad network. Currently, most areas of Pará and Mato Grosso lack connectivity to the railroad network, but recently, new railroad concessions have been approved to expand the railroad network to Pará and Mato Grosso. These include the connection of Maraba and Marcarena in Para, the expansion of the Railroad Paulista for connecting Rondopolis-Cuiaba-Nova Mutum in Mato Grosso. Also, in 2021 an auction was carried out for the concession EF-170/MT/PA, which will improve the connectivity of the grain-producing region to the river as port for exports.

With respect to land cover types, one limitation of this study is the aggregation of different land covers (other than Forest, Pasture, Crops, and Silviculture) into the "other" category. The way this aggregation was implemented in the land use model, allowed to focus the attention on access cost and the role of access cost on the transition from forest lands to lands in agriculture, but at the same time limited the ability to draw conclusions regarding the composition of "other" land cover. Another caveat of this study is that data on silviculture is scarce compared to the other land types, and the capacity of the model to predict land shares on that type of cover was affected.

Finaly, there are diverse potential extensions and applications of this work. For instance,this research could be extended to other areas of Brazil or regions in other countries. The Brazilian road network is one of the most extensive in the world (The World Bank, 2012). Most of the current network was established between the 1950s and the 1980s, but the dynamics of road improvement slowed during the subsequent 20 years. In the mid 2000s when only about 12% of the entire Brazilian road infrastructure was paved, new action plans and alliances with the private sector were initiated to boost infrastructure improvement (Amann et al., 2016). It is estimated that Brazil will require an investment of about R$4.1 trillion in logistics over the next 20 years to achieve a top 20 ranking in the Best Countries in Infrastructure (Duff & Phelps, 2018). Road infrastructure in Brazil will keep improving and some of those projects will likely pass through fragile ecosystems in the Amazon biome. Indeed the current administration of Bolsonaro has reactivated plans on road infrastructure such as the BR-319 that connects from south to north regions unexplored in the Amazon Biome and have relevant implications on deforestation.

The carbon tax/credit analysis could be expanded to other regions inside and outside Brazil. By 2020, 189 countries had ratified the Paris agreement, and the current framework could be applied as is for estimating the effects of road infrastructure on land use change on their context, and estimate the carbon tax levels required to mitigate to zero the excess in emissions from any road infrastructure improvement. Further research is also needed to determine the potential consequences of a tax/credit mechanism and determine if the tax would add an extra burden to the Brazilian farmers, the asymmetries between deforestation and reforestation to account for changes in carbon stocks, and the alteration of incentives due to carbon tax redistribution policies. Nonetheless, the methodology employed in Chapter 5 could be useful for other applications different than GHG emissions, it may be useful to estimate efficiency gains in economic activity, as data is available to connect land use change with the economic activity derived from it.

A further expansion of this research could add the impact of climate variables to sort out potential impacts of climate change on land use; e.g. currently, the cornbelt is situated in the midwestern US, however, with the raise of global temperatures, the corn belt could be expanded to other areas in Canada. Further research could also incorporate a disaggregated version of this model by including specific crops into the model.

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