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DISENTANGLING THE CONTRIBUTION OF CATTLE RANCHING TO DEFORESTATION IN THE BRAZILIAN AMAZON

Marcus Vinicius de Freitas Silveira

Master's Dissertation of the Graduate Course in Remote Sensing, guided by Dr. Luiz Eduardo Oliveira e Cruz de Aragão, approved in February 18, 2021.

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ABSTRACT

Deforestation rates have been rising in the Brazilian Amazon since 2013 and a long-term planning to reduce trends requires an in-depth understanding of the major drivers of land use change in the region, such as cattle ranching. However, there is a lack of large-scale evidence about how the technological and socioeconomic conditions in which cattle ranching is practiced influence on deforestation. This study assessed the contribution of different cattle ranching systems to deforestation in the Brazilian Legal Amazon from 2017 to 2019, and compared their trends in land use change and stocking rate across time intervals within the period from 2000 to 2019. Farming statistics were collected at the municipal level from Brazil's agricultural census of 2017. Municipalities with a predominance of cattle ranching farms were divided into four farming system groups, according to pairwise combinations of higher/lower than average levels of adoption of management practices and capital investment among farms. The highest deforestation rates were found for municipalities with a lower adoption of both management practices and capital investment. These municipalities also had a significantly lower density of slaughterhouses, and presented greater trends in forest loss since the 2008-2012 period compared to municipalities in the two farming system groups with a higher adoption of management practices. The proportion of municipalities with significant increases in stocking rate without significant increases in pasture area started to rise in all farming systems since the 2008-2012 period, but still accounted for only 21% of total municipalities during the 2012-2019 period. Agrarian settlements were the land tenure category with the highest likelihood for deforestation in all farming systems. Policies aiming to prevent deforestation could consider increasing the adoption of management practices among ranchers as one of the major strategies.

Keywords: Land use change. Deforestation drivers. Intensification. Sustainable agriculture. Stocking rate. Agricultural census. Time series. Land tenure. Agrarian settlements.

DISTINGUINDO A CONTRIBUIÇÃO DA PECUÁRIA BOVINA PARA O DESMATAMENTO NA AMAZÔNIA BRASILEIRA

RESUMO

As taxas de desmatamento têm aumentado na Amazônia brasileira desde 2013 e um planejamento de longo prazo para reduzir esta tendência requer um entendimento aprofundado dos principais fatores associados ao problema, como a pecuária bovina. Entretanto, há ainda uma falta de evidência em larga escala sobre como as condições tecnológicas e socioeconômicas da pecuária bovina influenciam no desmatamento. Este estudo avaliou a contribuição de diferentes sistemas de pecuária bovina para o desmatamento na Amazônia ocorrido entre 2017 e 2019, e comparou estes sistemas pelas suas tendências de mudança de uso do solo e taxa de lotação em intervalos temporais durante o período de 2000 a 2019. Estatísticas foram coletadas a partir do censo agropecuário brasileiro de 2017 em base municipal. Os municípios foram divididos em quatro sistemas de pecuária bovina, de acordo com combinações de níveis maiores/menores que o nível médio de adoção de práticas de manejo e investimento em capital entre as fazendas. As maiores taxas de desmatamento foram observadas para os municípios que tinham tanto uma menor adoção de práticas de manejo quanto de investimentos em capital. Estes municípios também tinham uma densidade significativamente menor de frigoríficos, e têm apresentado maiores tendências de perda florestal desde o período de 2005 a 2012 se comparados aos municípios dos dois sistemas de pecuária com maior adoção de práticas de manejo. A proporção de municípios com aumentos significativos na taxa de lotação sem aumentos significativos na área de pastagem começou a crescer desde o período de 2008-2012, mas ainda representou apenas 21% do total de municípios durante o período de 2012-2019. Os assentamentos rurais foram a classe fundiária com a maior propensão ao desmatamento em todos os sistemas de pecuária bovina. Políticas públicas voltadas para a prevenção do desmatamento poderiam considerar o aumento na adoção de práticas de manejo entre os pecuaristas como uma das estratégias mais importantes.

Palavras-chave: Mudança de uso da terra. Fatores associados ao desmatamento. Intensificação. Agricultura sustentável. Censo agropecuário. Série temporal. Estrutura fundiária. Assentamento rural.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACI	Adoption of Capital Investment
AMP	Adoption of Management Practices
CRZ	Cattle Ranching Zone
FFZ	Forest Formation Zone
INPE	Instituto Nacional de Pesquisas Espaciais
H-ACI	Higher Adoption of Capital Investment
H-AMP	Higher Adoption of Management Practices
L-ACI	Lower Adoption of Capital Investment
L-AMP	Lower Adoption of Management Practices
ROI	Region of Interest

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1 INTRODUCTION

After peaking in 2004, deforestation in the Brazilian Legal Amazon was drastically reduced over the next years through a series of intervention policies (WEST; FEARNSIDE, 2021), culminating in 2012 with the lowest annual deforestation record (INPE, 2020a). Since 2013, however, deforestation rates have been rising in the region and reached in 2020 the highest record since 2008 (INPE, 2020a). This upward trend is menacing as it brings an intensification of the associated negative impacts that extend beyond the well-known ecological ones (e.g., habitat loss and fragmentation), and include regional and countrywide climatic alterations, economic losses, and public health issues (COSTA et al., 2019; ELLWANGER et al. 2020; LEITE-FILHO et al., 2019; STRAND et al., 2018; SPRACKLEN et al., 2012). The trend also puts Brazil's agenda under the Paris Agreement for reducing greenhouse gas emissions into serious constraints. Although the country legally committed to reduce Amazonian deforestation in 2020 by 80% of the average from the 1995-2005 period (19,625 km²), the 11,088 km² of deforested areas in that year represented a reduction of only 43.5% (BRASIL, 2018; SILVA JUNIOR et al., 2020). If the country wants to accomplish its objective of being carbon neutral by 2060 (UNFCCC, 2020), the end of illegal Amazonian deforestation needs to be the utmost effort, as land use change has been the country's greatest source of carbon emissions, predominantly due to Amazonian deforestation (SEEG, 2020).

Combat operations for illegal deforestation play a crucial role in mitigating and inhibiting the problem, but a long-term planning for reducing deforestation trends essentially requires a thorough understanding of the associated drivers to support the creation of effective prevention policies. Remote sensing assessments have shown that most deforested areas in the Brazilian Legal Amazon are converted to pasture in the short-run and remain as pasture in the long-term (INPE, 2016; TYUKAVINA et al., 2017). The expansion of cattle ranching in the Amazon dates back to the 1970s, when the military regime created fiscal incentives to the migration of large-scale ranchers as part of the means to integrate the region with the rest of the country (CARVALHO et al., 2002). Aside for production, the expansion of pasture over forests was also largely motivated by land grabbing and speculation purposes, as cattle ranching is the most convenient mechanism to ensure land occupation (HECHT, 1993, MARGULIS, 2003).

Many studies have been placing a greater weight on cattle ranching for production purposes, rather than for land grabbing and speculation, for the contribution to deforestation in the Amazon since the 1990s (FEARNSIDE, 2005; KAIMOWITZ et al., 2004; MARGULIS, 2003. NEPSTAD et al., 2006). The existing body of literature provided further support for this idea by indicating that deforestation was strongly correlated with cattle price (BARONA et al. 2010; BARRETO et al. 2008), and herd size across municipalities and states (RIVERO et al. 2009; KAIMOWITZ et al. 2004). Moreover, some studies suggest that cattle ranching is economically attractive in the region (ARIMA; UHL, 1997; ARIMA et al. 2005; MARGULIS, 2003), has the greatest participation in the agricultural economy (CASTRO, 2013), and is part of the local culture (HOELLE, 2014). Margulis (2003) in addition argued that cattle ranchers are in fact the main end purchasers of grabbed land, using this resource as a means to continue increasing their production, which makes sense if we consider that deforested areas have been mostly occupied by pasture throughout the decades.

However, this study is centered on the principle that the contribution of cattle ranching to Amazonian deforestation cannot be generalized to the activity as a whole, since ranching is practiced in the region under diverse socioeconomic conditions and production systems (CARVALHO et al., 2020). For an effective implementation of policies directed to reduce the influence of cattle ranching on deforestation, it is important to identify which farming systems are most contributing to the problem and where are they most prevalent. At the same time, the identification of farming systems with lower contributions to deforestation can provide insights to prevention policies.

So far, the scientific literature has provided divergent opinions about the influence of a greater adoption of agricultural technologies and practices on deforestation (VILLORIA et al., 2014). Some studies point that better agricultural management practices (i.e., technological progress) can reduce the need for pasture expansion over forests because of higher productivity gains on existing lands (COHN et al., 2014; GARCIA et a., 2017; STABILE et al., 2020; STRASSBURG et al., 2014). Conversely, some studies argue that the higher profit from such gains in productivity will encourage more pasture expansion over forests, especially while land continues to be abundant and cheap (LINE CARPENTIER et al., 2000; CATTANEO 2001; MULLER-HANSEN et al., 2019; VOSTI et al., 2001). Most studies treating this issue were based on small-scale data and used econometric models; but evidence from large-scale observational data are still poorly assessed for the Amazon.

In this study, census and remote sensing data were linked with the goal of comparing deforestation rates and trends in land use change across municipalities in the Brazilian Amazon with different cattle ranching systems. With this general objective in mind, the study was guided by the following specific objectives:

a) To assess the relationship between the proportion of livestock farms and recent deforestation rates (2017-2019) across municipalities in the Brazilian Legal Amazon.

b) To compare recent deforestation rates across municipalities divided into four groups of cattle ranching farming systems, based on pairwise combinations of higher/lower adoption levels of management practices and capital investment among cattle ranching farms.

c) To assess the relative distribution of old-growth forest area and deforested area among land tenure categories for each group of farming systems.

d) To compare trends in pasture cover, old-growth forest cover and stocking rate among farming system groups over the period of 2000-2019.

2 LITERATURE REVIEW

2.1 The emergence of cattle ranching in Brazil

The introduction of cattle in Brazil is suggested to have occurred in the 1530s as a means for load transportation (DEAN, 1997). Among the first cattle ranchers were the Jesuits at the beginning of the XVII's century, who initially used cattle for subsistence purposes but eventually turned ranching into an economic asset (DOS SANTOS; VAINFAS, 2014; SCHWARTZ, 2014). As the economy of the Kingdom of Portugal developed in Colonial Brazil along the XVII's century, cattle ranching expanded in the Northeast to supply the Neo-European demand for meat, the internal and external market with leather and skin, and to assist labor in sugarcane plantations (GOUVEA; FRAGOSO, 2014).

The donation of lands from Colonial Brazil by the Portuguese monarchy was implemented under the condition that grantees should use the land for agricultural activities such as cropland farming or cattle ranching (FERRAZ, 2014). The latter was likely considered more practical by landowners, which attributed cattle farming to letting the cattle graze freely, without much concern with management practices aiming to sustain pasture productivity (DEAN, 1997; LINHARES, 1996). This notion pervaded over the centuries, so much that extensive livestock production, with low management levels, became mainstream throughout the Brazilian territory. The designation of lands favored the concentration of large areas per landowner, as the delimitation of lands usually consisted of natural landmarks such as rivers (FERRAZ, 2014). The Portuguese monarchy favored coastal lands in the Northeast of Brazil to be primarily reserved to cropland systems, which pushed cattle ranching into the region's backcountry (DA SILVA, 1997). A movement towards the interior of Brazil was likewise practiced in the Southeast, mainly as an escape to the court's bureaucracy, which hampered production through heavy taxation, in addition to product confiscation and compulsory recruitments to wars (DEAN, 1997).

Cattle ranching was primarily practiced in natural pastures (DA SILVA, 1997; DEAN, 1997), but due to overgrazing of more palatable species, ranches recursively applied fire to stimulate their regrowth, though causing pasture degradation over the years (DEAN, 1997). Cattle ranchers also faced severe problems with droughts and pests, especially Leaf-cutter ants of the genus Atta. All those factors contributed to cattle ranching moving the agricultural frontier forward into the country's interior, inevitably leading to conflicts with indigenous people for natural grasslands and finally to deforestation of old-growth forests (DA SILVA, 1997; DEAN, 1997). Consequently, cattle ranching also became a convenient mechanism used by colonizers to declare land occupation and accumulate lands (DA SILVA). Land concentration also turned into a strategic economic resource for large landholders through the common practice of land leasing, in which owners divided their herds and lands into the responsibility of third-party farmers (DA SILVA, 1997; LINHARES, 1996; SAMPAIO, 2014).

At the end of the 18th century, cattle ranching was already consolidated as a definite aspect of Brazil's economy, after large expansions had also occurred in the Southeast following mining activities (DEAN, 1997). It was during this century that cattle farms also started to be introduced in the Amazon, particularly on Marajo's island and other local centers, competing with northeastern farmers to supply the city of Belém (DA SILVA, 1997). The expansion of cattle ranching in the Amazonian territory began to take effect, however, in the late XIX's century with the boom of rubber production (DA SILVA, 1997), and then more significantly in the 1970s during colonization campaigns under the military regime (CARVALHO et al., 2002).

2.2 Perspectives on the effect of cattle ranching intensification on tropical deforestation

Agricultural intensification is defined as the increase in yield per unit of area (FAO, 2004). Although the application of technologies is one way for achieving this purpose, investing more time in production or adding labor forces can also lead to intensification (FAO, 2004). Some studies have also characterized intensification in livestock activities as the increase in stocking rate, which can turn unsustainable if above the site's carrying capacity or if not coupled with technology through good agricultural practices. Some ways to intensify cattle ranching production using technology include the use of improved animal breeds; improved grasses and legume forages; management practices such as rotational grazing and soil management; and inputs such as fertilizers for soils or dietary supplements for the animals (LATAWIEC et al., 2014). The implementation of these techniques can provide gains in productivity and land-use efficiency as improved forage grasses and legumes can be more resistant against pests, diseases, and climatic extremes; better soil and pasture management can reduce weed infestation, overgrazing, and soil compaction; and dietary supplements can provide better nutritional balance and liveweight gains for the animals (LATAWIEC et al., 2014). Field evidence from six projects promoting sustainable cattle ranching intensification in the Brazilian Amazon through the use of technologies and management practices point to observed increases in annual productivity in the order of 30-490% (ZU ERMGASSEN et al., 2018). Sustainable cattle ranching intensification also brings ecological benefits by improving hydrological regulation, increasing carbon sequestration by grasses and increasing carbon storage in soil (LATAWIEC et al., 2014).

Rises in profit are also expected with the adoption of better technological practices. The increase in productivity, combined with a lower average cost per animal, allow for better conditions for farmers to participate and compete in the market (STABILE et al. 2020; VILLORIA, et al., 2014). In the six on-the-ground projects across the Amazon promoting sustainable cattle ranching intensification that were reviewed by zu Ermgassen et al. (2018), participating farmers were able to increase their annual profits per hectare, on average, by 2-9 times. The initial investment required by these intensification projects ranged from R$ 1300-6900 per hectare, with an average payback period of 2.5-8.5 years. For most of these projects, zu Ermgassen et al. (2018) observed positive financial returns for both large and small-scale farming, though projects for the latter may present a greater risk of turning unprofitable, depending on the kind of system and technologies that will be implemented. Analyzing an intensification project involving pasture restoration, rotational grazing and good agricultural practices, Garcia et al. (2017) estimated the project would be unprofitable in farms with less than 426 ha of pasture. The authors estimated mean annual transition costs in the order of US$1335/ha ± US$619/ha, of which 50% was for restoration of protected areas to comply with environmental regulation, other 32% for pasture restoration and the final 22% for the implementation of good agricultural practices. The authors observed that costs were higher in the smallest participating farms in part because they also presented the highest levels of pasture degradation, surpassing 50% of pasture area.

Low-income farmers generally face great challenges in the Amazon from lacking technical assistance; difficulties in accessing market and credit; and high costs for technological inputs. Extensive means of production are then used as the most viable alternative, thought inevitably leading to pasture degradation over time, hindering production capacity. Farmers then deforest new areas to expand pasture, or not uncommonly, sell their properties to wealthier farmers and migrate further into the interior, leading to new deforestation frontiers (GARCIA et al., 2017; LATAWIEC, 2014; STABILE et al., 2020; WHITE et al., 2001). Such issues are strongly pervasive in Brazil's official agrarian settlements in the Amazon region, which accounted for around 30% of recent Amazonian deforestation (STABILE et al., 2020). But as observed by Costa (2009), extensive production and pasture degradation also occurs among high income ranchers. The author analyzed data from the Agricultural Census of 1996 and found that cattle density actually decreased as the scale of production increased. Increases in stocking rate became effective only in farms with more than 8,000 cattle heads.

Costa (2009) also observed that cattle ranches whose production is made by hired work force composed 6% of all farms in the Amazon in 1996, but detained 60% of farmland areas and 70% of degraded areas. For high income cattle ranching systems, extensive production could be seen as a deliberate process still considered to be the cheapest alternative, as forestlands are abundant and cheap, or because expansion can act as a mechanism for land-tenure security and land speculation (COSTA, 2009; KAIMOWITZ; ANGELSEN, 2008; MARCHAND, 2012). From 2001 to 2007, the price of forestlands in the Amazon was on average 57% and 77% lower than that of pasturelands and croplands, respectively (COSTA, 2009). Analyzing results of the Agricultural Census of 2006 for the Amazon, De Souza et al. (2013) found deforestation to be positively related to land ownership and land concentration, but negatively related to production value per hectare and income. The authors pointed that a considerable part of counties with the highest rates of land concentration and the lowest rates of productivity were in the arc of deforestation.

Because intensification through technological practices can reduce the magnitude and speed of pasture degradation, farmers would not need to clear new lands due to low productivity and financial returns. In addition, technological intensification can require higher investments in capital, time and skilled labor per hectare, encouraging ranchers to focus resources on already established lands (CATTANEO, 2001; GARCIA et al., 2017; KAIMOWITZ; ANGELSEN, 2008; VOSTI et al., 2001). All those factors contribute to the idea that intensification can spare the deforestation of additional areas. Angelsen and Kaimowitz (2008) believed this effect would be especially valid for smallholders that live close to the subsistence level and only use family labor. Pasture expansion could also be discouraged after intensification if increasing production per unit of area reduces beef price, which would be the case if the amount that people purchase remains relatively unchanged and if products are destined to local markets (GARCIA et al., 2017; KAIMOWITZ; ANGELSEN, 2008). Martha Junior et al. (2012) estimated that an additional 71 million hectares could have been deforested in the Amazon in the period of 1996-2006 had pasture expansion been the only means for reaching the livestock production rates of 2006, without accounting for the cattle ranching intensification that occurred during this period. Cohn et al. (2014) projected land-use change outcomes in Brazil for a scenario of subsides to semi-intensive cattle ranching and found that, from 2010 to 2030, 15 million hectares of forests would be spared and 212 Mt CO_2 eq of global greenhouse gas emissions would be avoided.

Contrary to this positive effect of intensification, some scientists argue that after increasing revenue with the adoption of better technological practices, farmers are motivated to expand pasture within and out of their properties to continue increasing their income, especially in areas with weak governance such as the Amazon (LINE CARPENTIER et al., 2000). Considering deforestation also demands investments in capital, farmers that intensified their production and thus increased their income are now less financially constrained to clear new lands (KAIMOWITZ; ANGELSEN, 2008). Kaimowitz and Angelsen (2008) also argue that certain technologies, such as shifting forage to a more productive kind, require relatively low investments to be purchased while releasing maintenance costs and labor, which could be allocated to deforestation. If intensification reaches the point of bringing economic development to the region where it occurs, resources such as in-migration and infrastructure projects would bring additional deforestation (KAIMOWITZ; ANGELSEN, 2008; CATTANEO, 2001). Nonetheless, Villoria et al. (2014) believe regional intensification can indirectly relieve pressure on forests in other parts of the country or even the globe because of market influences. Barreto et al. (2013) observed that while most regions in Brazil had an increase in pasture yield from 1996-2006 in spite of contractions in pasture area, both pasture yield and area predominantly increased in the Amazon, which they attributed to the abundance and low-cost of lands. Similar conclusions were taken by other studies, which reinforced that the land-sparing effect of agricultural technology will not be effective while regulation of occupied public lands continues to be flexible and forestland price continues to be cheap (KAIMOWITZ; ANGELSEN, 2008; MULLER-HANSEN et al., 2019; VILLORIA, et al., 2014). White et al. (2001) hypothesized that technology would only be largely adopted when forests become scarce. The authors analyzed study cases from Peru, Costa Rica and Colombia, in sites with different stages of market development and land-use history, and found that farmers continued with extension practices as long as forestland prices rose to the point that technological intensification was the cheapest alternative.

The thought foundation for the increased-deforestation hypothesis after technological intensification came from a series of studies compiled by Angelsen and Kaimowitz (2001) at the beginning of 21st century. Those studies were important for cautioning against unexpected outcomes from intensification, providing information that should be taken into consideration in policy-making and conservation planning. But into what extent their rationale can be generalized for the Brazilian Amazon? Following the premise that a continuous maximization of profit is the ultimate goal after intensification, we may also consider that ranchers could invest in more profitable and less land-demanding agricultural activities, instead of keeping expanding pastures. Based on a case study in the Amazonian state of Mato Grosso, Dos Reis et al. (2019) found that productivity in a typical livestock extensive system of production was five times lower than in an integrated crop-livestock system (ICL), providing financial returns substantially lower than both ICL and a typical crop system.

In addition, since 2004 many progresses have been made in terms of deforestation control in the Brazilian Amazon, to the point that in 2008 deforestation rates were already 34% below the average from 1996-2005 (19,625 km²), and 77% below in 2012. Territorial planning was greatly improved by PPCDAm, and remote sensing advances allowed near-real time monitoring of deforestation events (WEST; FEARNSIDE, 2021). Moreover, an environmental decree (Decree nº 6.514/2008) created in 2008 provided a better characterization of how penalties should be applied, enforcing sanctions such as fines and embargoes. In case of serious efforts towards the implementation of deforestation command and control initiatives, as occurred from 2004 to approximately the beginning of the 2010s decade in Brazil, ranchers therefore can be greatly discouraged to spend profits from intensification into further land clearing.

Market policies are also an important mechanism to help preventing deforestation among farmers, such as the soy moratorium created in 2006 and the beef moratorium created in 2009. The beef moratorium refers to agreements with the government, set by slaughterhouses in the Amazon, to stop the purchase of cattle coming from farms with deforestation after 2009 and not registered in the Rural Environmental Registry (CAR) (GIBBS et al., 2016). Since 2009, at least 75% of federally inspected slaughterhouses in the Amazon participate in the beef moratorium (ALIX-GARCA; GIBBS, 2017). Surveying a large sample of farms in the state of Pará that were directly supplying to slaughterhouses, Gibbs et al. (2016) found that the proportion of supplying farms with recent deforestation declined from 36% in 2009 to 4% in 2013. Despite its potential positive effect on reducing deforestation, the beef moratorium is subjected to deforestation leakages because slaughterhouses only monitor direct suppliers, though deforestation can occur in indirect supplying farms and direct suppliers can participate in cattle laundering with indirect suppliers (GIBBS et al., 2016). Therefore, it is essential to include the entire supply chain in the monitoring of slaughterhouses, rather than only direct suppliers, to better guarantee the land-sparing potential of the moratorium (GIBBS et al., 2016).

2.3 Deforestation timeline in the Brazilian Legal Amazon

Deforestation trends in the Amazon have long been represented in many studies as bar charts showing annual rates over a given time period, although information on what could be influencing variations in magnitude across the years has been vague and highly scattered. The rate and speed of land clearing processes inevitably reflect dynamics of a society's political and economic spheres. In this section I provide a comprehensive representation of the full extent of temporal trends in Amazonian deforestation (Figure 2.1), indicating policies and laws implemented along the years that could have directly or indirectly influenced in the dynamics. Annual deforested areas were collected by PRODES monitoring program, which commenced its activities in 1988. As observed in the figure, some policies seem to create a non-negligible response in deforestation rates, not necessarily immediately but in an expected time-delay considering the efforts to implement actions. This is mostly evident for the series of policies in the 2000s that were crucial to redefine escalating trends, though this effect lost strength in the next decade in part due to counteracting policies.

Figure 2.1. A policy-guided visualization of annual deforestation rates in the Brazilian Legal Amazon.

Policies that can help reducing deforestation rates were highlighted in green. PPCDam refers to the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon. DETER refers to the program for daily deforestation alerts based on remote sensing monitoring and coordinated by Brazil's National Institute for Space Research (INPE). Policies for a given year were implemented at any period from January to December.

Source: Produced by this author.

In the 1970s, Brazil's military regime started to implement a series of intervention strategies to settle the Amazonian region and promote its economic development, such as the construction of federal highways (e.g. Cuiabá-Porto Velho BR-364, Cuiabá-Santarém BR-163, Trans-Amazon BR-230), and fiscal incentives to basic service sectors (CARVALHO et al., 2002). Large scale cattle ranching projects were one of the major beneficiaries from the incentives and deforestation expanded alongside roads, also fueled by land speculation and the income of migrants (CARVALHO et al., 2002). In the 1980s, Brazil entered into an economic recession that increasingly aggravated over the decade; this process was followed by a reduction in deforestation rates, probably due to the reduction of capital inflow (FEARNSIDE, 2005). In June of 1991, the government created a decree suspending the concession of fiscal incentives to projects that required deforestation of old-growth forests (BRASIL, 1991).

In 1994, the government created a series of economic reforms under the Real Plan to control the hyperinflation, leading to a peak in the deforestation in 1995 with the increase of capital inflow. Fearnside (2005) points that land price also peaked in 1995, but fell by 50% at the end of 1997, making land speculation less attractive. In 1998, environmental legislation advanced in Brazil with the Law nº 9.605 for environmental crimes (BRASIL, 1998), which brought clear definitions about sanctions such as that for illegal deforestation. In 2000, the country established the framework for its National System of Nature Conservation Units – SNUC (BRASIL, 2000), indicating the criteria for the creation and management of protected areas. In 2003, cattle herds in the states of Mato Grosso, Rondônia and Tocantins were declared free from Foot-and-Mouth disease, allowing these states to export beef to other Brazilian states and to the international market (KAIMOWITZ et al., 2004). No longer after, the state of Acre and the south of Pará were also allowed for beef exportation.

After deforestation in the Amazon reached in 2004 the second highest rate since the start of monitoring in 1988, the government created the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm). The program was divided into four phases (I: 2004-2008, II: 2009-2011, III: 2012-2015, IV: 2016-2020), and promoted strategies into three themes: land planning; monitoring and control; and promotion of sustainable production activities (BRASIL, 2016). During the first phase, some of the many significant outcomes were the creation of 50 million ha of protected areas, the homologation of 10 million ha of indigenous lands, and the creation of DETER, a near-real time deforestation monitoring system based primarily on MODIS satellite imagery (WEST; FEARNSIDE, 2021).

The agricultural market also contributed to conservation efforts with the creation of the soy moratorium in 2006, in which major soy-traders agreed to stop buying from properties in the Brazilian Amazon biome with deforestation after 2006. In

2007, the government created a policy to reinforce monitoring for priority municipalities in terms of deforestation, imposing greater restrictions to access of credit for farmers in these municipalities (BRASIL, 2007). In addition, the law of environmental crimes was reinforced in 2008 through better definitions for the application and payment of sanctions (BRASIL, 2008b). In 2009, major meatpacking companies in the Brazilian Amazon signed Terms of Adjustment of Conduct with the federal government, agreeing to stop buying from properties with illegal deforestation after 2008 (also known as the beef moratorium).

In 2012, Brazil's Forest Code was updated (BRASIL, 2012) and granted amnesty from sanctions to farmers that agreed to register their properties in the Rural Environmental Registry (CAR) and reforest the areas of their properties in debt with the environmental legislation. In 2017, the government authorized the regularization of public lands illegally occupied up to 2008 that had up to 2,500 ha through the purchase at very low prices (BRASIL, 2017), which could have encouraged further land grabbing in the subsequent years in hope for similar retribution. Since 2008, the government had been raising donations through the Amazon Fund to investments in conservation, deforestation monitoring and control (BRASIL, 2008a). However, the fund has been paralyzed since 2019 by the government, impeding the utilization of R$ 2.9 billion that were already donated by Norway and Germany (OC, 2021). PPCDAm was also paralyzed in 2019, summed with increasing reductions since 2015 in the amount of environmental sanctions that have been sued annually for infringements to the flora (OC, 2021).

3 DATA AND METHODS

3.1 Datasets

3.1.1 Deforestation of old-growth forests

Spatial data for annual old-growth deforestation from 2017 to 2019 were collected from PRODES Amazonia (INPE, 2020b), which is Brazil's official deforestation monitoring program for the Amazon. PRODES maps clear-cut areas based on photointerpretation of satellite images from the Landsat Program, which have a 30m spatial resolution (INPE, 2019). PRODES Amazonia is restricted to areas under the geographic range of forest formations and only maps deforestation of old-growth forests. PRODES data for a given year (reference year) correspond to deforestation events that occurred approximately from August 1 of the previous year to July 31 of the reference year (INPE, 2019). Every year the mapping uses an updated mask of the old-growth forest boundaries from which previous deforested areas were removed. Thus, areas that were once deforested are not mapped again.

3.1.2 Pasture area

Pasture area from 2000-2019 was collected from MapBiomas - Collection 5 Version 1 (MAPBIOMAS, 2020a), which is a multi-institutional remote-sensing initiative that produces annual land use and land cover maps of Brazil spanning from 1985 onwards. MapBiomas' mapping is based on Google Earth Engine's cloud platform and employs a Random Forest supervised classification of satellite images from the Landsat Program. Certain land use classes such as pasture have a separate classification approach and are subsequently integrated with the other mapped classes. Overlaps among classes are handled according to a class hierarchy and specific prevalence rules. Pasture for instance has priority over natural forests, but not over cropland classes (MAPBIOMAS, 2020b).

The classification of pasture on a pixel basis involved the use of 76 metrics (74 statistical measures of spectral bands and indices, and four spatial metrics) as inputs, calculated over a 24-month time-window. For every scene, pixels were classified as pasture or not-pasture after the algorithm was trained with samples randomly distributed over the adjacent scenes. Each one of these samples was visually inspected by three interpreters who analyzed two Landsat scenes per year (one in the wet season and another in the dry season), in addition to MODIS NDVI time series and high-resolution Google Earth images. The accuracy assessment was performed with 5,000 validation samples (2,500 for pasture and 2,500 for not-pasture) that were visually inspected by five interpreters through the same approach described above.

The overall classification accuracy of pasture is approximately 91% across the time series. The user accuracy, which indicates the proportion of pixels classified as pasture that are indeed pasture according to real observations, is approximately 92%. The producer accuracy, which indicates the proportion of real pasture observations correctly classified as pasture, ranges from 60-72%. This means that pasture areas as shown in the maps are mostly reliable to real observations, but are likely underestimated given that around 28-40% of real pasture observations were misclassified as other land uses. For more information about the classification scheme for pasture areas, see MapBiomas (2020c).

Pasture as classified by MapBiomas is based on the following description given by the initiative: “pasture areas, natural or planted, related to farming activity” (MAPBIOMAS, 2020b). However, it is difficult to guarantee through a remote-sensing approach that all areas classified as pasture are actually being used for farming, especially when the classification is mostly automated such as in the case of MapBiomas. Thus, one caveat concerning this data is the possible inclusion of abandoned pasture or of early forest regrowth into what has been classified as pasture. Nonetheless, MapBiomas is continuously improving the quality of its mapping, which constitutes the only dataset providing consistent annual land use and land cover information of Brazil.

3.1.3 Cattle ranching statistics

I collected and processed several variables related to cattle ranching from Brazil's Agricultural Census of 2017 (IBGE, 2020a), which was conducted by the Brazilian Institute of Geography and Statistics (IBGE). This census investigates Brazil's agrarian system by gathering characteristics of farms, agricultural activities and people involved in farming. Farms in this sense consisted of any unit dedicated totally or partially to agricultural production, independently of its size, location or legal situation. The census approach for data collection consisted of in-person structured interviews about statistics from a reference period from October 1, 2016 to September 30, 2017. Although interviews were conducted in every Brazilian farm, publicly available data is assembled and provided at the municipal level.

In addition, I calculated the stocking rate per municipality in 2017 by diving the census information on number of cattle by pasture area in this same year according to MapBiomas classification. I also calculated the density of slaughterhouses and nearest Euclidean distance to slaughterhouses per municipality, according to spatial information provided by the Amazon Institute of People and the Environment (IMAZON) about all active slaughterhouses operating in the Brazilian Legal Amazon in 2016 (IMAZON, 2020). The complete list of 22 variables and their description are in Table 3.1 below:

Table 3.1. List of variables about cattle ranching farming that were used in this study.

VARIABLE	UNIT	DESCRIPTION	SPECIFICATION	STUDY SITES
Cattle raising farms	% farms	proportion of farms raising cattle.		Municipalities in the Forest Formation Zone*
Livestock farms	% farms	proportion of farms with livestock as the predominant production activity.		
Cooperative	% farms	proportion of farms in general participating in agricultural cooperatives.		Municipalities in the Cattle Ranching Zone**
Credit	% farms	proportion of livestock farms that used credit.	derived from any agent: banks, cooperative, enterprises, etc.	
Dairy production	% farms	proportion of cattle ranching farms raising cattle for dairy production.		
Dietary supplementation	% farms	proportion of farms in general that used dietary supplements for livestock.	any salt, grains, silage or other agro-industrial subproduct.	
Family farming	% farms	proportion of cattle ranching family farms.	definition is in accordance to law nº 11.326/06: a farm which predominantly uses family labor, the income comes predominantly from farming activities and farm size is up to 4 fiscal modules (one fiscal module varies from 5-110 hectares, depending on the municipality).	
Farms with production	% farms	proportion of livestock farms that sold big animals and/or produced milk during the reference period.		
Fertilization	% farms	proportion of farms in general that applied fertilizers.	any chemical or organic fertilizer.	
Land ownership	% farms	proportion of cattle ranching farms whose production is carried by the legal landowner.	farms in which the leading producer is also the legal landowner, alternative options include land-leasing contracts, illegally occupied farms, etc.	
Liming	% farms	proportion of farms in general that applied lime.		
Mean farm area	ha/farm	average farm area per livestock farm.	total area occupied by livestock farms, divided by the number of livestock farms.	
Nonfamily labor	% farms	proportion of cattle ranching farms that hired nonfamily employees.		
Pasture degradation	% farms	proportion of cattle ranching farms in which the farmer reported having pastures in bad conditions.	this variable was self-declared by the producer. Degradation here refers to pasture under bad conditions due to the absence of management, leading to weed invasion or soil erosion for example.	
Production value	R$ x 1000/farm/year	estimated monetary value of livestock production per livestock farm.	total monetary return from sale of big animals and the monetary value of milk production, divided by the total number of livestock farms.	
Slaughterhouse density	number of slaughterhouses/ 100km	number of slaughterhouses in a radius of 100 km from the municipality border.	Active slaughterhouses in 2016 were collected from IMAZON geoportal (IMAZON, 2020).	
Slaughterhouse distance	km	nearest distance in km to slaughterhouses.	Euclidean distance from a municipality border to the nearest slaughterhouse. If there is any slaughterhouse within a municipality, then the value is 0.	
Stocking rate	head of cattle/ha	number of cattle per hectare of pastureland.	Pasture area in 2017 was obtained from MapBiomas.	
Tractor	% farms	proportion of livestock farms that have one or more tractors.		
Technical assistance	% farms	proportion of livestock farms that received technical assistance.	includes any responsible institution: government, NGO, enterprises, etc.	
Tillage	% farms	proportion of farms in general that did tillage practices.	includes conventional tilling, minimum tilling or conservation tilling practices.	
Workers density	workers/farm	average number of people working in production per livestock farm.	total number of people working in livestock farming production, divided by the number of livestock farms.	

*This study refers to Forest Formation Zone as the set of selected Amazonian municipalities with 80% of their area in the natural range of forest formations and at least 10% of their area still covered by old-growth forests in 2016 (Figure 3.1).

**This study refers to Cattle Ranching Zone as the sub selection of municipalities in the Forest Formation Zone in which at least 75% of farms raised cattle and had livestock as the predominant production activity (Figure 3.1).

Source: Produced by this author.

3.1.4 Land tenure

Spatial data for Brazilian land tenure boundaries were collected from the Atlas of Brazilian Agriculture (IMAFLORA, 2020). This project provides an integrated map of all official datasets about Brazil's public and private land boundaries, allocating land into a hierarchy of 14 tenure categories. The hierarchy was based on the level of land tenure security and the likelihood of future transition to another land tenure category. In case of spatial overlaps among land tenure categories, priority was given to the category of higher-ranking. For more information about this dataset, see Sparovek et al. (2019) and Freitas et al. (2018). In this study I assembled land tenure categories from the Atlas into five classes, defined as follows:

- Certified private lands: private properties with land rights certified by Brazil's National Institute for Colonization and Agrarian Reform (Incra). It includes the *SIGEF/SNCI* and *Terra Legal Titulado* land tenure categories from the Atlas.
- CAR – Rural Environmental Registry: private properties with boundaries self-declared by the landowner and registered in the Rural Environmental Registry program, but not certified by Incra. It includes the *CAR poor* and *CAR premium* land tenure categories from the Atlas.
- Agrarian settlements: properties originally owned by the federal government that are assigned to farmers for agrarian reform purposes. Farmers can acquire land rights in due course.
- Undesignated public lands: lands owned by the federal government that still did not receive an official designation. It includes the *SIGEF/SNCI Público*, *Terra Legal Não Titulado* and *Florestas Tipo B* land tenure categories from the Atlas.
- Unregistered lands: public lands that were not covered by any category of the Atlas and are not registered in any official database.

3.1.5 Old-growth forest time series

PRODES mapping of annual deforestation commenced in 1988, but annual deforestation data in electronic format is only available from 2000 onwards. Moreover, PRODES data for old-growth forest boundaries are provided in the program's platform only for the 2016 to 2019 period. The old-growth forest boundaries in 2016 represent the remaining forest area after deforestation mapped up to 2016 (according to PRODES calendar). To obtain annual estimates of old-growth forest area from 2000 to 2019 per municipality, I first calculated the municipalities' old-growth forest area in 2000 by summing their old-growth forest area in 2016 with their total deforested area from 2001 to 2016 as mapped by PRODES. For the subsequent years, the old-growth forest area was obtained by cumulatively subtracting the deforested area in each corresponding year.

3.1.6 Stocking rate time series

For the time series analyses, I collected the annual number of cattle per municipality from Pesquisa Pecuária Municipal - PPM (IBGE, 2020b), an initiative from IBGE that provides annual estimates of livestock population per municipality since 1974. PPM obtains head of cattle estimates through interviews with institutions responsible for vaccination campaigns against Foot-and-mouth disease, in addition to other public and private entities, farmers and technicians. I used head of cattle estimates for the time window of 2000 to 2019. To obtain annual stocking rate estimates for each municipality, I divided the number of cattle by pasture area in hectare from MapBiomas for each corresponding year of the time series.

3.2 Study sites

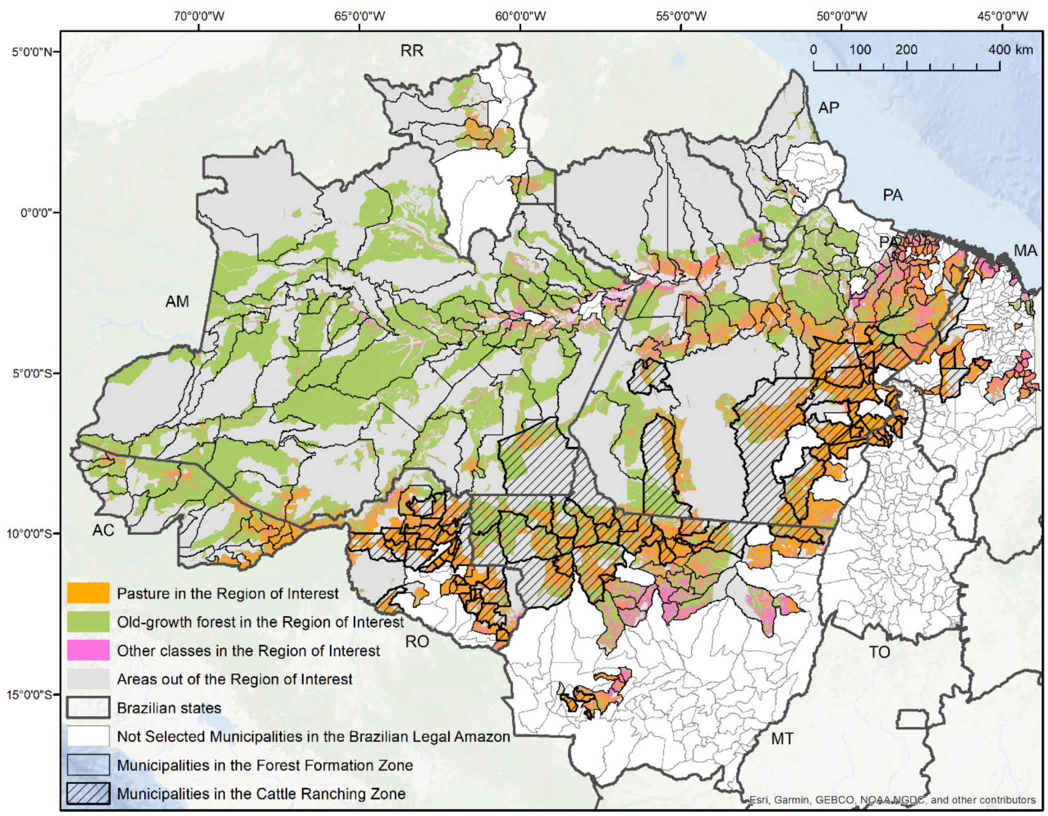
This study used municipalities of the Brazilian Legal Amazon as samples, as this was the scale from which cattle ranching data from IBGE'S Agricultural Census of 2017 is available. The comparison of deforestation rates across municipalities is subjected to biases that need to be addressed to guarantee reliable interpretations. Some municipalities for example have most of their forest area in protected areas or indigenous lands, which are land tenure categories presenting a lower likelihood of deforestation and pasture expansion. In addition, forests are not the predominant natural vegetation for part of Amazonian municipalities, while there are some municipalities with very little old-growth forest cover left. All these factors can directly influence in the comparison of deforested area among municipalities.

To address these biases, I defined a Region of Interest (ROI) within municipalities where annual deforestation rates and old-growth forest area were extracted. This ROI covers the areas under the natural range of forest formations, excluding protected areas (with the exception of *Áreas de Proteção Ambiental – APA*, the least strict protected area category in Brazil), indigenous lands, water bodies and rocky outcrops (Figure 3.1).

Next, I defined two sets of municipalities to use as samples in the analyses. In the first set I selected municipalities in the Brazilian Legal Amazon with at least 80% of their area under the natural range of forest formations and at least 10% of old-growth forest cover in their ROI in 2016. This set, referred throughout the study as municipalities in the Forest Formation Zone (FFZ), comprises 352 municipalities out of the 772 of the Brazilian Legal Amazon (Figure 3.1). I used the FFZ municipalities to assess the relationship of deforestation with the proportion of livestock farms across municipalities.

To evaluate which socioeconomic factors and farming systems of cattle ranching are most related to deforestation, I used a second set of municipalities selected from FFZ municipalities. For this second set, referred throughout the study as municipalities in the Cattle Ranching Zone (CRZ), I selected the 80 municipalities in which at least 75% of farms raise cattle and have livestock as the predominant production activity (among all agricultural production activities in a farm, that with the greatest monetary value), and pasture is the predominant agricultural land use based on a visual inspection of MapBiomas classification of 2017. These criteria were necessary because statistics for some variables of the Agricultural Census refer to farms in general, while others refer to livestock farms, and others specifically to livestock farms that raise cattle. By selecting the municipalities that are strictly cattle ranching dominant, I therefore ensure that statistics from the Census are actually referring to cattle ranching farms, regardless of the level of data specification. The municipalities in the Cattle Ranching Zone are located in consolidated areas of the agricultural frontier, mostly in the region considered the Arc of Deforestation, where most historical deforestation occurred.

Figure 3.1. Study sites and illustration of the Region of Interest.



Source: Produced by this author.

3.3 Annual deforestation rates

Comparing municipalities by their deforested area leads to bias because municipalities have different sizes and consequently different old-growth forest areas. In this sense, a municipality can have a greater deforested area than another, but the actual proportion of forest that was lost can be lower because of their different old-growth forest areas. To address this issue, municipalities in this study were compared by their relative annual deforestation rate, given by the mean deforestation from 2017-2019 divided by the old-growth forest area in 2016, according to the following formula:

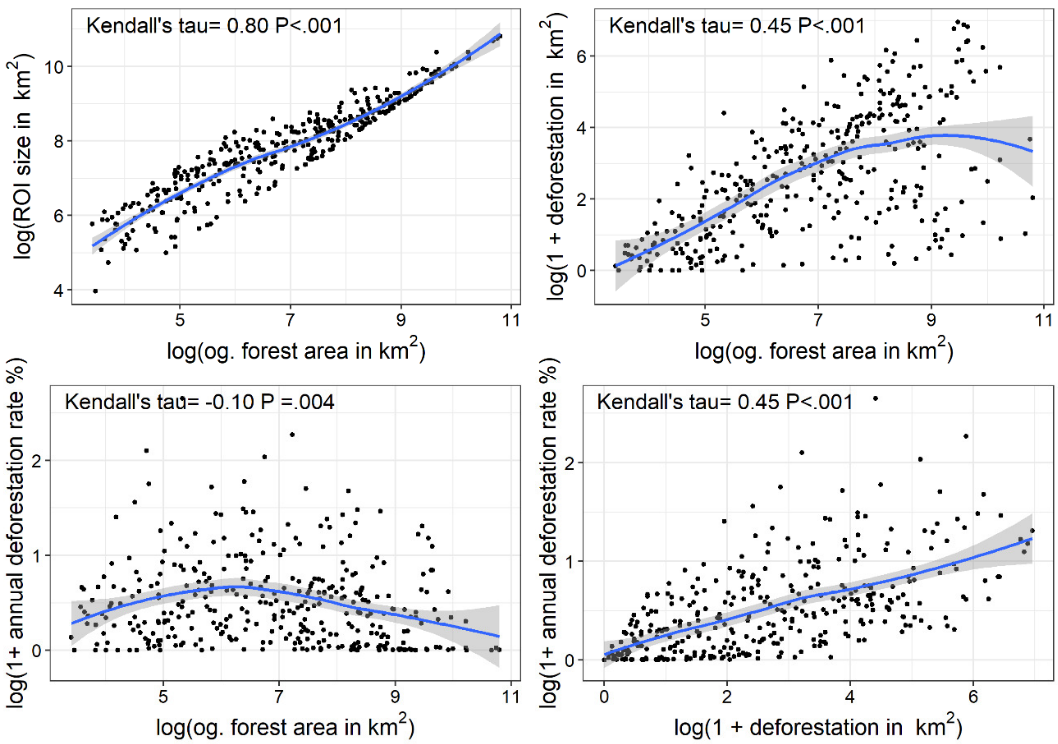
$$\text{Annual deforestation rate (\%)} = \frac{1}{\mathrm{F}}\left(\frac{\mathrm{D}_1 + \mathrm{D}_2 \ldots + \mathrm{D}_\mathrm{n}}{\mathrm{n}}\right) \cdot 100 \qquad (3.1)$$

where F is the old-growth forest area prior to the analyzed period of deforestation, D values are the annual deforestation in each respective analyzed year, and n is the number of years in the analyzed period.

This metric indicates the average proportion of old-growth forest that was annually cleared during the period of 2017-2019, allowing us to assess the intensity with which forests were lost across municipalities. The use of an average proportion of forest loss instead of the total in the three analyzed years was chosen because it reduces the effect of outliers and gives weight to the annual frequency of deforestation.

As shown in Figure 3.2, the old-growth forest area in municipalities is highly associated with the size of their ROI (Kendall's tau = 0.8, P<.001). By comparing municipalities by annual deforestation rates instead of gross deforestation, the association with old-growth forest area is greatly reduced (Kendall's tau from 0.45 to -0.01, P<0.001 and P=.004 respectively), while the association between annual deforestation rates and gross deforestation remains relevant (Kendall's tau= 0.45, P<001).

Figure 3.2. Associations among the size of a municipality's Region of Interest (ROI), the old-growth forest area (km²), total deforested area (km²) from 2017-2019 and the annual deforestation rate (%).



Values were log transformed for visualization purposes. Blue lines represent the estimated trend of the relationship based on a locally weighted smoothing (LOWESS), and shade represents the confidence interval for a 95% confidence level.

Source: Produced by this author.

3.4 Correlation analysis

Using the 352 municipalities in the Forest Formation Zone as samples, I evaluated how the proportion of livestock farms is related to the annual deforestation rate and to the ratio of pasture area over old-growth forest area. While the annual deforestation rate represents more recent deforestation events (2017-2019), the pasture/forest ratio indicates the relative extent of pasturelands and thus of historical forest conversion in municipalities. Both old-growth forest area and pasture area refer to the year of 2016. To control for the influence of old-growth forest area into the strength and direction of relationships, I assessed separate correlations for three groups of municipalities divided by the following intervals of old-growth forest area: 30-300 km², 300-3000 km², and more than 3000 km². These intervals guaranteed that each group contained at least 100 samples.

For the set of 80 municipalities in the Cattle Formation Zone, I assessed relationships among 20 variables (Table 3.1) representing several socioeconomic and production aspects of cattle ranching, and the relationship of each with annual deforestation rate. These variables are either proportions or ratios, most of them indicating the proportion of farms with a certain attribute (e.g., the variable fertilization indicates the proportion of farms in a municipality that used fertilizers).

The strength of relationships was measured with Kendall's tau rank correlation (KENDALL, 1938). Contrary to Pearson's product moment correlation, Kendall's tau does not assume data to have a bivariate normal distribution, in addition to being more robust against outliers and non-linearity (NEWSON, 2002). Such parameters are important in this study because the annual deforestation rates have a highly skewed distribution with the presence of outliers. Croux and Dehon (2010) in addition demonstrated that Kendall's tau is more robust against outliers and more statistically efficient than Spearman's rank correlation, which is a more popular non-parametric correlation coefficient. Kendall's tau ranges from -1 to 1 and can be interpreted in simple terms as the difference between the percentage of concordant pairs (observations from both variables move in the same direction) and the percentage of discordant pairs (observations from both variables move in opposite directions) in the data.

3.5 Index development

I combined some of the collected variables from the Agricultural Census (Table 3.1) to calculate two indices for the municipalities in the Cattle Ranching Zone. These indices provide a way to summarize the high amount of socioeconomic information collected in this study and, when analyzed together, they give an overview about the different farming systems in which cattle ranching is practiced in the Amazon. One index measures the degree of adoption of management practices (AMP) among farms, and the other measures the degree of adoption of capital investment (ACI) among farms, in a given municipality.

The adoption of management practices (AMP) index is composed of the following variables: dietary supplementation, fertilization, liming, technical assistance and tillage. Values for each of one these variables represent the proportion of farms in a given municipality that adopted them. The use of dietary supplements can promote liveweight gains and nutritional balance for the cattle, while fertilization, liming and tillage can promote greater forage productivity, reducing weed infestation and soil compaction (LATAWIEC et al., 2014). Technical assistance is a complementary variable in this index because through such service farmers can receive technical knowledge or supervision to promote better pasture management.

The Adoption of Capital Investment (ACI) is composed of the following variables: credit, land ownership, nonfamily labor, production value and tractor. Each one of these variables also represent the proportion of farms that adopted them, except for production value that represents the average monetary value of cattle ranching production per farm. With the use of credit, farmers have more money to invest in their production, such as with increasing herd size or buying machinery. The variable production value takes into account cattle sales and/or the amount of milk production, thus indicating the scale of production and consequently farmers' wealth. The hire of nonfamily labor and the ownership of tractor provide an indication that farmers may be investing a great amount of capital in their production. Lastly, nonfamily labor indicates the proportion of farms in which the producer is also the landowner, which indirectly tells us about the economic power of farmers, since farmers that do not own their lands are more financially constrained to invest in their production.

These indices are calculated by summing their five corresponding variables, with the application of relative weights for each variable. Each variable originally ranged from 0 to 1, as they represent proportion of farms, except for the variable production value from which values were brought into this range through a min-max rescaling. I applied relative weights to the variables from the same index based on the absolute Kendall's tau correlation coefficient between a given variable and the annual deforestation rate, divided by the sum of absolute correlation coefficients of all variables from the corresponding index. This way, variables that are more related to deforestation have more importance in the calculation, which helps clarifying which variables could receive priority for policies aiming at reducing deforestation. After weighting, each index ranged from 0 to 1. The greater the index value of a municipality, the greater the adoption among farms of the five variables that compose each index. The formula of each index is as follows:

Adoption of Management Practices (AMP) Index = *(3.2)*

w_i . dietary supplementation + w_i . fertilization + w_i . liming +

w_i . technical assistance + w_i . tillage

Adoption of Capital Investment (ACI) Index = *(3.3)*

w_i . credit + w_i . land ownership + w_i . nonfamily labor +

w_i . production value + w_i . tractor

where w_i denotes the relative weight of variables from the same index, calculated as follows:

$$w_i = \frac{|tau_i|}{\sum |tau_i|} \qquad (3.4)$$

where $|tau_i|$ is the absolute Kendall's tau correlation coefficient between the corresponding variable and annual deforestation rate

Next, I assessed the Kendall tau correlation between the two indices and compared their Kendall tau correlation with annual deforestation rate. In addition, I compared the distribution of annual deforestation rates between municipalities grouped by higher or lower levels of each index, according to index values above or below the median respectively. Groups were compared with pairwise non-parametric Wilcoxon rank-sum tests at the 5% significance level.

3.6 Comparisons across cattle ranching farming systems

I classified municipalities in the Cattle Ranching Zone into four farming system groups, according to all pairwise combinations of higher (H) and lower (L) levels (above or below the median, respectively) of the Adoption of Management Practices (AMP) index and the Adoption of Capital Investment (ACI) index, as follows: H-AMP H-ACI, H-AMP L-ACI, L-AMP H-ACI, and L-AMP L-ACI.

I used pairwise Wilcoxon rank-sum tests at the 5% significance level to compare these groups for differences in annual deforestation rate, old-growth forest area, and the total 20 socioeconomic variables from the correlation analyses. To verify if differences in deforestation at the municipal level are consistent with those at a finer scale, I also compared the groups for annual deforestation rates calculated at the census tracts level. These tracts are subdivisions of a municipality's territory that are used by the Agricultural Census to facilitate the registry and control of collected data. Each census tract can have from 100 to 200 farms and an area of up to 5000 km².

In a second approach, for each group I assessed the relative distribution of old-growth forest area (2016) and total deforested area (2017-2019) across five land tenure categories: certified private lands, CAR – environmental rural registry, agrarian settlements, undesignated public lands, and unregistered lands (see section 3.1.4 for a full description). The idea is that if all these land tenure categories had the same likelihood of deforestation, their proportional share of the total deforested from 2017-2019 in a given farming system group would be similar to their proportional share of the total old-growth forest area available in 2016. In contrast, a given land tenure has a greater likelihood of being deforested if its proportional amount of deforested area is greater than its proportional amount of old-growth forest area.

3.6.1 Trend analysis

I compared the four farming system groups by their trends in old-growth forest cover, pasture cover and stocking rate during the following time intervals: 2000-2004, 2004-2008, 2008-2012, and 2012-2019. These time intervals were chosen for presenting more concordant trends in deforestation for the whole Brazilian Legal Amazon (INPE, 2020a), which is important to guarantee more reliability in the estimates. The chosen time thresholds also reflect important events for deforestation dynamics in the region. In 2004, the peak in deforestation led to the creation of the Action Plan for the Creation and Control of Deforestation in the Legal Amazon – PPCDAm (BRASIL, 2016). The program was divided in four phases, with the first phase finished in 2008, and the second phase finished in 2011. In 2012, total deforestation was the lowest on record, but still in this year Brazil's Forest Code was updated (BRASIL, 2012), granting amnesty to sanctions from farmers that deforested prior to 2008 but agreed to register their properties in the Rural Environmental Registry (CAR) and reforest the areas of their properties in debt with the environmental legislation.

For each municipality, I calculated the slope of the time series in each time interval with the nonparametric Sen's slope estimator and assessed the statistical significance of monotonic increasing or monotonic decreasing trends with the Mann-Kendall test. The Sen's slope is estimated as the median of slopes $(Y_j-Y_i)/(t_j-t_i)$ from all pairs of time series elements, being more robust against outliers than slopes estimated by least squares linear regression (SEN, 1968). I used pairwise Wilcoxon rank-sum tests at the 5% significance level to compare the distribution of slopes across the farming system groups.

4 RESULTS

4.1 Deforestation statistics across the study sites

From 2017 to 2019, a total area of 21,076 km² was deforested in the Region of Interest of the 352 municipalities in the Forest Formation Zone (FFZ). This represents 84% of total deforestation in the Brazilian Legal Amazon for the same period (including areas outside of the region of interest). The median annual deforestation rate among municipalities was 0.52%, with rates for most municipalities below 1% (third quartile).

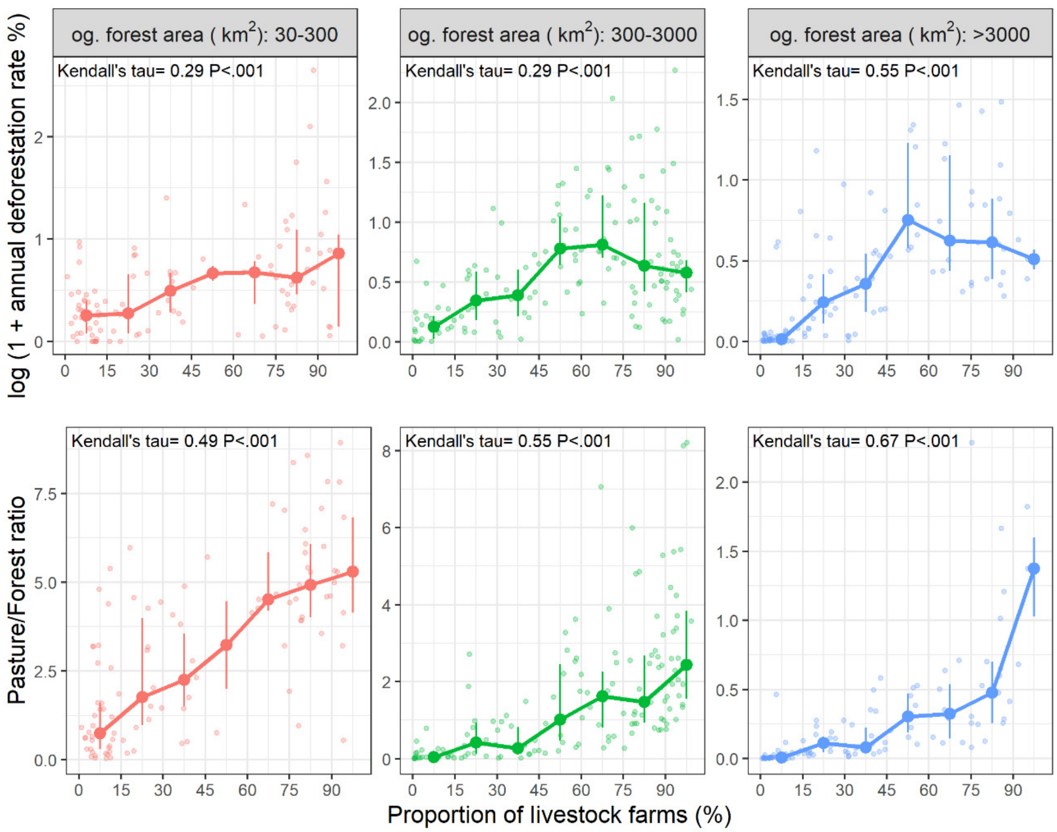
The set of 80 municipalities in the Cattle Ranching Zone (CRZ) concentrated one third of total deforestation from municipalities of the FFZ from 2017-2019, and 27% of total deforestation in the Brazilian Legal Amazon. The median annual deforestation rate in these municipalities was 0.88%, with most rates below 2% (third quartile). Municipalities in the CRZ represented 46% of all in the FFZ with annual deforestation rates greater than 2% (11 out of 19), and 77% of all with annual deforestation rates greater than 4% (7 out of 9).

Considering the total extension of the Region of Interest, old-growth forests and pasturelands in 2016 covered respectively 70% and 21.6% of the FFZ, whereas both old-growth forests and pasturelands covered 47% of the CRZ. Of the total area deforested from 2017-2019, 77% were converted to pasture in the FFZ, and 86% in the CRZ. The average proportion of deforested area converted to pasture across municipalities in the FFZ was 73%, in contrast to 90% across municipalities in the CRZ.

4.2 The relationship of livestock farming and deforestation

Of the total number of farms in the FFZ (506,242), 43.5% (220,301) had livestock as the major production activity, with an average proportion of 45% livestock farms per municipality. The association of annual deforestation rate and proportion of livestock farms across municipalities was positive and statistically significant at the 5% level, regardless of the range of old-growth forest area across municipalities (Figure 4.1). The strength of association was greater for municipalities with more than 3000 km² of old-growth forest (Kendall's tau = 0.55, P<.001), compared to those with an area of 300-3000 km² or 30-300 km² (Kendall's tau = 0.29, P<.001 for both cases).

Figure 4.1. The response of annual deforestation rate and pasture/forest ratio to the proportion of livestock farms in a municipality, according to three ranges of old-growth forest area.



Points in the curve represent the median value for each 15% bin of the proportion of livestock farms; the lower and upper edges of vertical lines across points represent the first and third quartile, respectively. Kendall's tau correlations coefficients for the relationships are also shown. Annual deforestation rate values were log transformed for visualization purposes.

Source: Produced by this author.

The peak in median annual deforestation occurred at the 90-100% bin of proportion of livestock farms for municipalities with 30-300 km² of forest area, at the 60-75% bin for municipalities with 300-3000 km², and at the 45-60% bin for municipalities with more than 3000 km². In these last two ranges of forest area, median annual deforestation rates decreased after the peak but remained above those of municipalities with less than 45% of livestock farms.

The ratio of pasture/forest was significantly positively associated with the proportion of livestock farms for the three ranges of old-growth forest area. The strength of association gradually increased from municipalities in the lowest to the greatest range of forest area (Kendall's tau = 0.49, 0.55 and 0.67, for the three ranges of old-growth forest area in ascending order; all P values <.001).

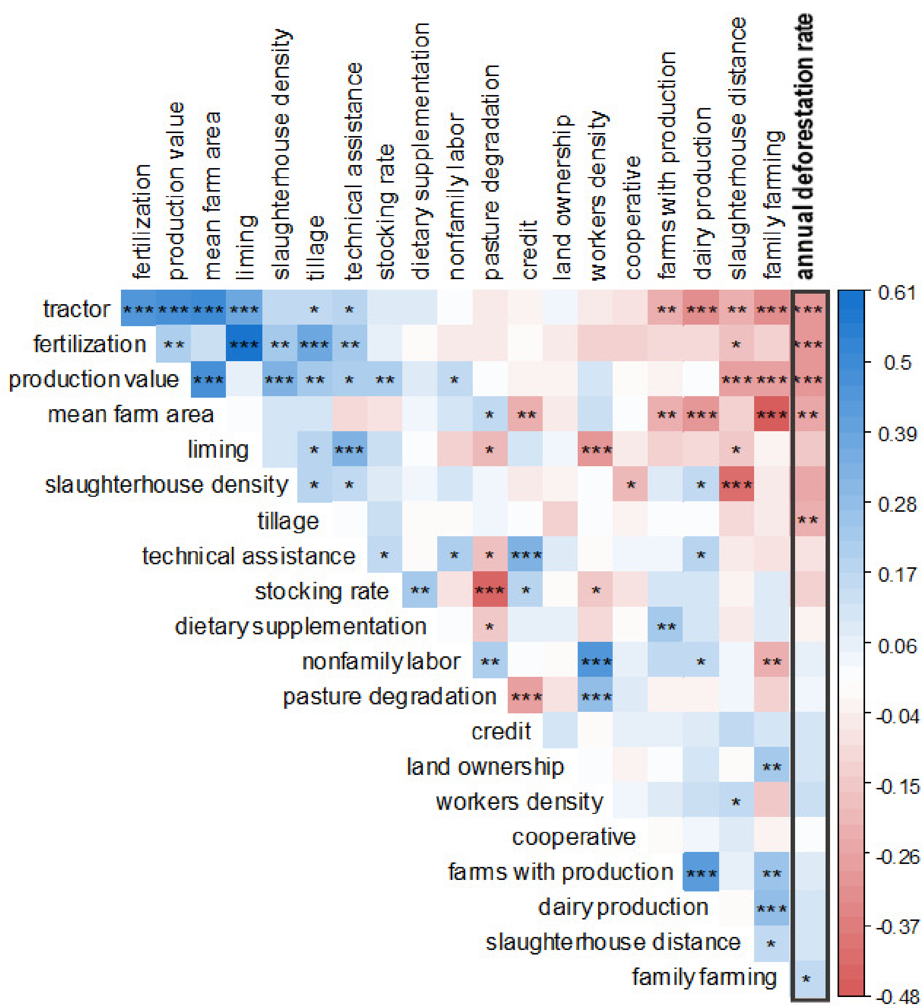
4.3 Correlations among cattle ranching factors and deforestation

The 80 municipalities in the Cattle Ranching Zone comprise an estimated number of 102,000 cattle ranching farms. Based on the histogram of cattle ranching variables (Appendix Figure A.1), these farms are mainly composed of family farms with legal land rights and a small-numbered labor force, actively producing but under low levels of technology, capital and community-association. For instance, on average 73% of farms in a municipality were family farms, 81% of livestock farms produced in 2016-2017 (sale of big animals and/or production of milk), and the producer was the landowner in 87% of farms. However, only 15% of farms on average used fertilizers or received technical assistance, and 14% had tractors.

The variables mean farm area, production value and proportion of farms with tractor were all significantly positively associated at the 5% level (Figure 4.2). Significant positive associations were also found among family farming, dairy production and the proportion of farms with production; and among tillage, fertilization, and liming. These last two were also significantly positively related to technical assistance. Fertilization and production value were significantly positively related to slaughterhouse density, and significantly negatively related to slaughterhouse distance. Pasture degradation was significantly positively related to mean farm area and nonfamily farming; and significantly negatively related to liming, technical assistance, stocking rate, dietary supplementation and credit.

Out of the 20 variables, only seven were significantly associated with annual deforestation rate. Fertilization, tractor and production value had the strongest associations (Kendall's tau = -0.30 and P<.001 for all), followed by slaughterhouse density (Kendall's tau = -0.26, P=.001), mean farm area (Kendall's tau = -0.25, P=.001), tillage (Kendall's tau = -0.22, P=0.004), and family farming (Kendall's tau = 0.15, P=0.046).

Figure 4.2. Correlation matrix of annual deforestation rate and 20 socioeconomic variables related to cattle ranching.



Values in the vertical bar indicate the magnitude of Kendall's tau correlation coefficient. Significant correlations at the 5% level are marked with asterisks, and the number of asterisks refer to the magnitude of P values as follows: * = P<.05; ** = P<.01; *** = P<.001).

Source: Produced by this author.

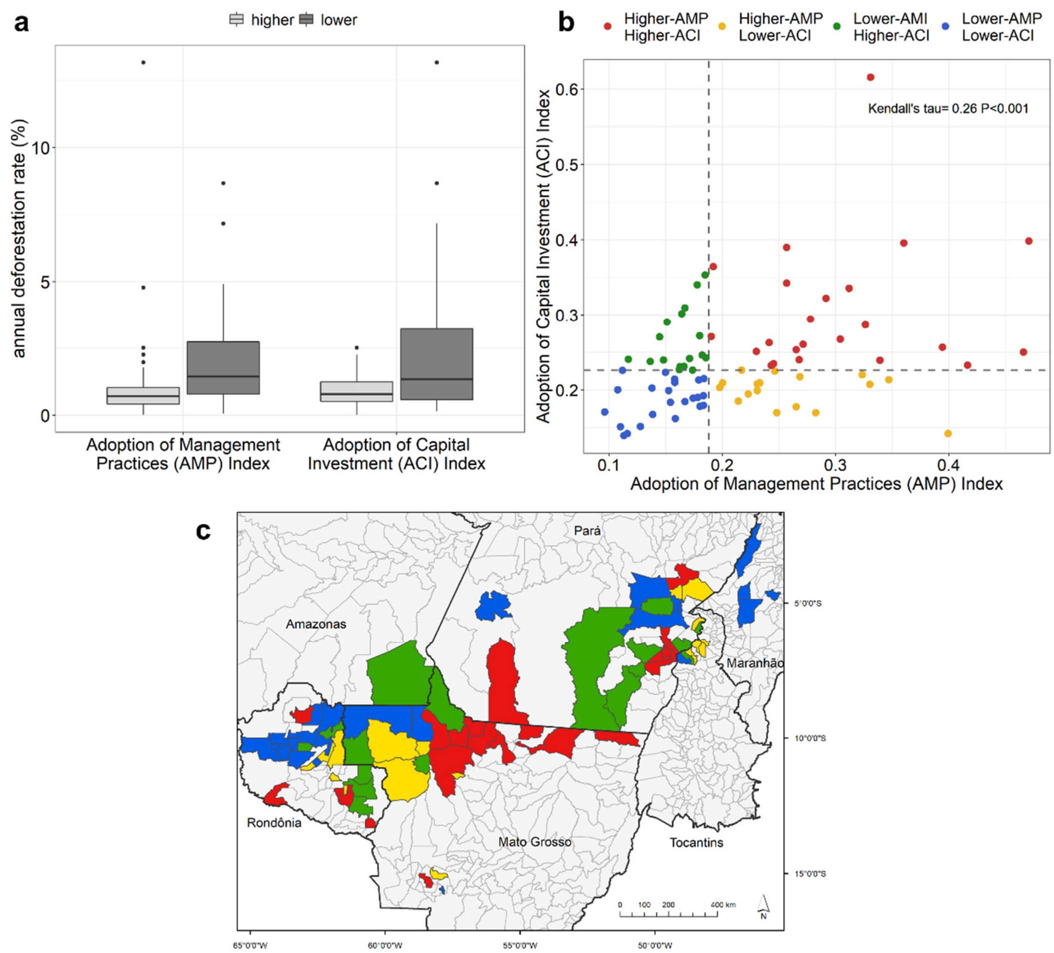
4.4 The relationship of farming system indices and deforestation

Values for the Adoption of Management Practices (AMP) index ranged from 0.10 to 0.47 across municipalities, with a median value of 0.19; whereas values for the Adoption of Capital Investment (ACI) index ranged from 0.14 to 0.62 and had a median of 0.23. The greater the value of these indices, the greater the adoption of the five variables that compose each index. According to the index weighting based on Kendall's tau correlation coefficients between the variables and annual deforestation rate, the AMP index was mainly driven by the variables fertilization and tillage, and the ACI index by the variables production value and tractor.

For both indices, the distribution of annual deforestation rates was significantly different at the 5% level between municipalities divided by higher (above the median) and lower (below the median) index values ($P<.001$ for the AMP index and $P=0.016$ for the ACI index). As shown in Figure 4.3a, municipalities with a lower AMP index had a median annual deforestation rate two times greater than those with a higher index (1.44 against 0.7). In contrast, municipalities with a lower ACI index had a median annual deforestation rate 1.7 times greater than those with a higher index (1.34 against 0.78). Likewise, the AMP index had a stronger correlation with annual deforestation rate than the ACI index (Kendall's tau = -0.28 $P<.001$ and Kendall's tau = -0.19, $P=0.01$).

Although there is a significant association between the two indices, they do not share a high degree of dependance (Kendall's tau= 0.25, p-value<0.001), which allowed for the classification of four farming system groups with a fair distribution of municipalities (Figure 4.3b). Municipalities with a higher AMP index and a higher ACI index (H-AMP H-ACI group) were 23 in total, mostly present in northern Mato Gross state (Figure 4.3c). Municipalities with a lower AMP index and a lower ACI (L-AMP L-ACI group) index were also 23 in total, mostly present in the region comprising northern Rondônia and northwestern Mato Grosso. The other two farming system groups (H-AMP L-ACI and L-AMP H-ACI) had each 17 municipalities that were well distributed across states.

Figure 4.3. (a) Box plots showing the distribution of annual deforestation rates for municipalities divided by higher (above the median) and lower (below the median) levels of farming system indices. (b) The relationship between the AMP Index and the ACI index, with the corresponding Kendall's tau correlation coefficient. (c) The spatial distribution of the four farming systems across municipalities in the Brazilian Legal Amazon.



Dashed lines represent the median value for each index, which was the parameter to define higher and lower levels of each index for the classification of four farming system groups.

Source: Produced by this author.

4.5 Comparisons among farming system groups

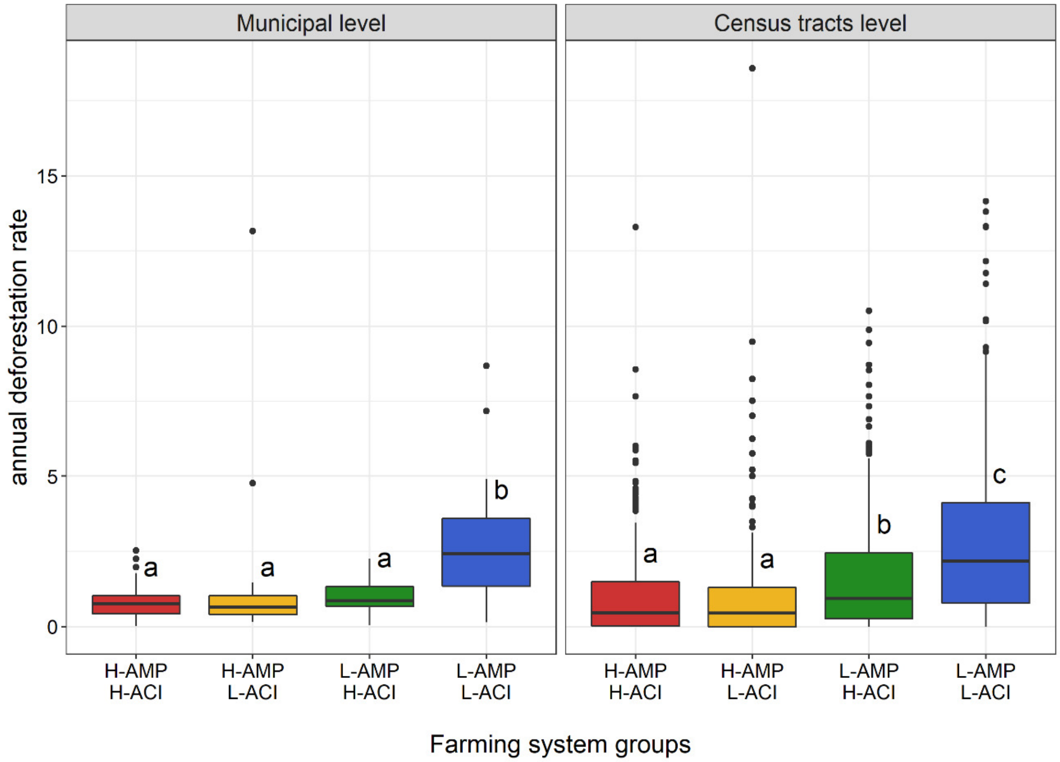
Among the four farming system groups, the distribution of annual deforestation rates was only significantly different at the 5% level in municipalities with a lower adoption of both management practices and of capital investment (L-AMP L-ACI).

Municipalities in this group had a median annual deforestation rate of 2.43%, a value three times greater than in H-AMP H-ACI municipalities, 3.8 times greater than in H-AMP L-ACI municipalities, and 2.85 times greater than in L-AMP H-ACI municipalities. If we take into account the total deforested from 2017-2019 in each group, L-AMP L-ACI municipalities had 2731 km² and L-AMP H-ACI municipalities had 2170 km², in contrast to 1337 km² in H-AMP H-ACI municipalities and 678 km² in H-AMP L-ACI municipalities.

Municipalities in the L-AMP L-ACI group also significantly differed from those of all other groups by having in general a lower density of slaughterhouses, a lower average production value, and a lower proportion of farms with tractor. In addition, these municipalities significantly differed from municipalities in H-AMP groups by being in general more distant to slaughterhouses. The two L-ACI groups had a significantly lower mean farm area, and the old-growth forest area across groups was only significantly lower in H-AMP L-ACI municipalities. Results for all the assessed variables and the corresponding mean values across groups can be found in Appendix Table A.1.

When annual deforestation rates were compared at the finer scale of census tracts (a subdivision of municipalities in which each tract has up to 200 farms and a maximum area of 5000 km²), rates in L-AMP L-ACI were also significantly higher than those in other groups (Figure 4.4). In addition, rates in L-AMP H-ACI were significantly higher than those in H-AMP groups. The proportion of census tracts in each group that had deforestation from 2017-2019 was 91% for L-AMP L-ACI, 88% for L-AMP H-ACI, 75% for H-AMP L-ACI, and 79% for H-AMP H-ACI.

Figure 4.4. Box plots of annual deforestation rate at the municipal level and census tracts level for each farming system group.



Each census tract has up to 200 farms and a maximum area of 5000 km². H and L stand respectively for higher and lower than average. AMP stands for Adoption of Management Practices and ACI stands for Adoption of Capital Investment. Letters represent statistical differences among groups at the 5% level.

Source: Produced by this author.

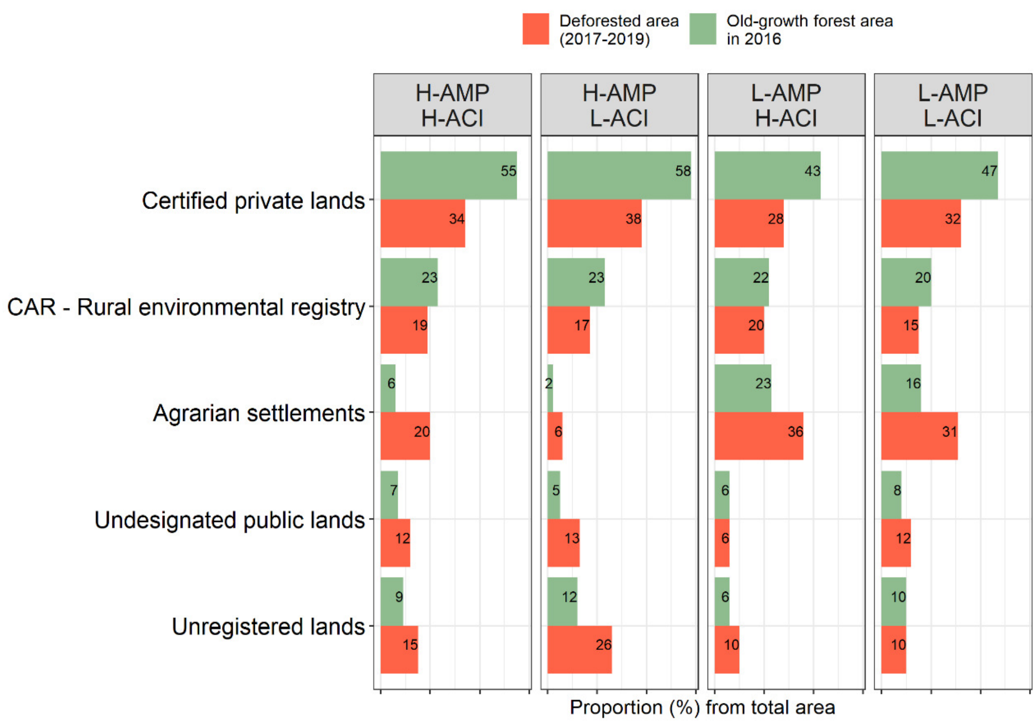
4.6 Relative distribution of deforested area and old-growth forest area across land tenure categories

Overall, the four farming system groups showed similar relative distributions of total deforested area and total forest area among the land tenure categories, especially between groups with the same categorization (higher or lower levels) for the adoption of management practices index. The most notorious differences among groups were observed in agrarian settlements, followed by unregistered lands.

Certified private lands held more old-growth forest area in 2016 than any other land tenure category, especially in the H-AMP groups where it held more than 50% of their total old-growth forest area, but contributed to a substantially lower proportion of the total deforested area from 2017-2019. Still, this tenure category was the one with the greatest proportion of deforested area in all but the L-AMP H-ACI group (Figure 4.5).

Private lands only registered in the Rural Environmental Registry (CAR) program had the least contrasting differences between the proportion of deforested area and the proportion of forest area among groups, which suggests that this land tenure had a greater likelihood of being deforested than certified private lands.

Figure 4.5. For each one of the four groups of municipalities divided by farming systems, their relative distribution of total deforested area from 2017-2019 and their relative distribution of total old-growth forest area in 2016 across land tenure categories.



H and L stand respectively for higher and lower than average. AMP stands for Adoption of Management Practices and ACI stands for Adoption of Capital Investment.

Source: Produced by this author.

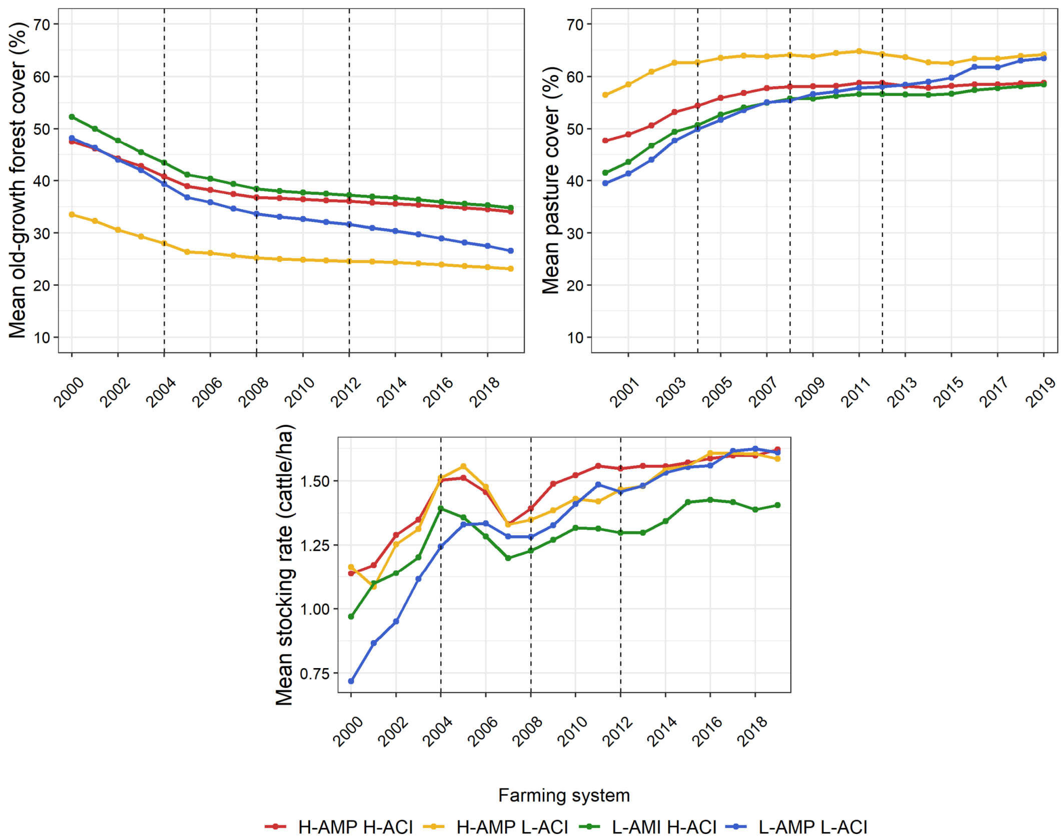
Agrarian settlements were the land tenure with the greatest likelihood of being deforested, regardless of the farming system group. The proportion of deforested area within this land tenure was three times greater than the proportion of old-growth forest area for H-AMP municipalities, 1.56 times greater for L-AMP H-ACI municipalities, and 1.93 times greater for L-AMP L-ACI municipalities. This land tenure was the one with the greatest proportion of deforested area (36%) in L-AMP H-ACI municipalities, and basically tied with certified private lands in L-AMP L-ACI municipalities despite having two times less proportion of forest area. In L-AMP H-ACI for instance, agrarian settlements and CAR lands had similar proportions of forest area, but the proportion of deforested area in agrarian settlements was 1.8 times greater.

In undesignated public lands, the proportion of deforested area was equivalent to the proportion of forest area for L-AMP H-ACI municipalities, and greater for the other groups, especially for H-AMP L-ACI municipalities where it was 2.6 times greater. This last group was also was the one in which unregistered lands had the greatest likelihood of being deforested, as the proportion of deforested area was more than twice that of forest area.

4.7 Land use change trajectories across farming system groups

As shown in Figure 4.6, at the beginning of the time-series the farming system groups of municipalities already diverged in terms of the mean old-growth forest cover, pasture cover and stocking rate. The H-AMP L-ACI group presented a much lower mean old-growth forest cover, the L-AMP groups presented a lower mean pasture cover, and the L-AMP L-ACI presented a much lower stocking rate. However, the distribution of slopes for forest cover trends during the first time interval (2000-2004) was not significantly different at the 5% level among groups. During this period, the groups lost on average 1.4-2.2% of their old-growth forests per year (Table 4.1).

Figure 4.6. Time series of old-growth forest cover (%), pasture cover (%), and stocking rate (head of cattle/ha) for municipalities divided into four farming system groups.



H and L stand respectively for higher and lower than average. AMP stands for Adoption of Management Practices, and ACI stands for Adoption of Capital Investment. Dashed lines illustrate the four time intervals used in trend analyses: 2000-2004, 2004-2008, 2008-2012, 2012-2019.

Source: Produced by this author.

For the 2004-2008 time interval, forest cover slopes for L-AMP L-ACI municipalities were significantly more negative (i.e., greater forest loss because slopes for this variables are either zero or negative) than those for H-AMP L-ACI municipalities, but not significantly different from those in the other groups at the 5% level. During this interval, average forest cover slopes for the groups were about half of those from 2000-2004 (Table 4.1). In the two following time intervals (2008-2012, 2012-2019), forest cover slopes for L-AMP L-ACI municipalities were significantly more negative than those for H-AMP municipalities, but not significantly different from L-AMP H-ACI municipalities. Figure 4.6 illustrates how the L-AMP L-ACI group remained with an accentuated forest loss during these last two time intervals, while forest loss for the other groups was less steep. Average slopes of forest cover from 2008-2012, compared to 2004-2008, further increased (i.e., less forest loss) by 2.5 times in L-AMP L-ACI and by 3.5 times or more in the other groups. From 2012-2019, all groups had decreases in the average slopes of forest cover compared to 2008-2012, in the order of 50% for H-AMP groups, 20% for L-AMP H-ACI and 40% for L-AMP L-ACI.

Table 4.1. Mean slopes (% change/year) for time series intervals of old-growth forest cover, pasture cover and stocking rate across municipalities divided into four farming system groups.

Variable	Time Interval	H-AMP H-ACI	H-AMP L-ACI	L-AMP H-ACI	L-AMP L-ACI
old-growth forest cover	2000-2004	-1.64^{a}	-1.38^{a}	-2.22^{a}	-2.19^{a}
	2004-2008	-0.81^{ab}	-0.5^{a}	-1.02^{ab}	-1.25^{b}
	2008-2012	-0.18^{a}	-0.14^{a}	-0.28^{ab}	-0.5^{b}
	2012-2019	-0.27^{a}	-0.21^{a}	-0.34^{ab}	-0.7^{b}
pasture cover	2000-2004	1.76^{a}	1.62^{a}	2.46^{ab}	2.67^{b}
	2004-2008	0.9^{ab}	0.23^{a}	1.22^{ab}	1.42^{b}
	2008-2012	0.23^{a}	0.13^{a}	0.27^{a}	0.6^{b}
	2012-2019	0.08^{a}	0.07^{a}	0.31^{a}	0.87^{b}
stocking rate	2000-2004	0.08^{a}	0.09^{a}	0.07^{a}	0.12^{a}
	2004-2008	-0.04^{a}	-0.05^{a}	-0.05^{a}	0^{b}
	2008-2012	0.03^{a}	0.03^{a}	0.02^{a}	0.05^{a}
	2012-2019	0.01^{a}	0.02^{a}	0.02^{a}	0.03^{a}

Slopes were calculated with the Sen's slope estimator. H and L stand respectively for higher and lower than average. AMP stands for Adoption of Management Practices and ACI stands for Adoption of Capital Investment. Letters indicate whether there is a statistically significant difference at the 5% level in the distribution of slopes across farming system groups.

Source: Produced by this author.

Negative trends in forest cover were significant at the 5% level for all municipalities in the 2000-2004 time interval (Appendix Table A.2). From 2004-2008, significantly negative trends were found for all municipalities in the H-AMP and L-AMP H-ACI groups, and for 96% of L-AMP L-ACI municipalities (all but one municipality) in this and the following time intervals. From 2008-2012, 87% of H-AMP H-ACI municipalities and 88% of H-AMP L-ACI municipalities had significant trends in forest cover, whereas the corresponding proportion from 2012-2019 was 96% for H-AMP H-ACI and 100% in H-AMP L-ACI.

Pasture cover slopes were significantly greater in L-AMP L-ACI municipalities compared to those for H-AMP groups in the 2000-2004 time interval, significantly greater than those for H-AMP L-ACI municipalities in the 2004-2008 time interval, and significantly greater than those for all other groups in the 2008-2012 and 2012-2019 time intervals. The average pasture cover slope from 2004-2008 was reduced by about half of the value from 2000-2004 in the H-AMP H-ACI and L-AMP municipalities, and seven times reduced in H-AMP L-ACI municipalities. Average slopes further reduced by about half from 2008-2012 compared to 2004-2008 in L-ACI municipalities, and by about four times in H-ACI municipalities. Further reductions occurred during 2012-2019 compared to 2008-2012 in H-AMP municipalities, particularly H-AMP H-ACI, while L-AMP municipalities had an increase in the average slope, particularly L-AMP L-ACI.

Over the three time intervals comprising the period from 2000 to 2012, the proportion of municipalities with significantly positive trends in pasture cover was highly reduced in all farming system groups This reduction was more relevant during the 2004-2008 period for H-AMP L-ACI municipalities, more relevant during 2008-2012 for H-ACI municipalities, and totally concentrated during 2008-2012 for L-AMP L-ACI municipalities. However, from 2012-2019 all farming system groups had an increase in the proportion of municipalities with significantly positive trends in pasture cover, compared to 2008-2012. This increase was from 30% to 35% in H-AMP H-ACI, 6% to 29% in H-AMP L-ACI, 35% to 41% in L-AMP H-ACI, and 39% to 74% in L-AMP L-ACI. A complete report of the proportion of municipalities across groups with significant trends for each time interval and for each variable can be found in Appendix Table A.2.

Slopes of stocking rate were not significantly different among groups across all time intervals, with the exception of 2004-2008. During this period, L-AMP L-ACI municipalities had significantly greater slopes than all other groups. The average stocking rate slope for L-AMP L-ACI was zero during this period, while the other groups had exceptionally negative average slopes. There was an increase in the average stocking rate slopes from 2008-2012 compared to 2004-2008 in all groups, but a subsequent decrease in 2012-2019 in all groups but L-AMP H-ACI municipalities.

During the 2000-2004 and 2004-2008 time intervals, less than 30% of municipalities in each group had significantly positive trends in stocking rate, while at least 70% of municipalities in each group had nonsignificant trends. The proportion of municipalities with significantly positive trends increased in 2008-2012 compared to 2004-2008 for the H-AMP and L-AMP H-ACI groups, and further increased in all groups but H-AMP L-ACI from 2012-2019. From 2012-2019, municipalities with significantly positive trends in stocking rate ranged from 24-30% in H-AMP groups and from 41-48% in L-AMP groups. The proportion with either nonsignificant or negative trends ranged from 70-76% in H-AMP groups and from 52-59% in L-AMP groups.

For the municipalities in each farming system group with significantly positive trends in stocking rate, the vast majority also had significantly positive trends in pasture cover in the 2000-2004 and 2004-2008 periods. However, during 2008-2012 and 2012-2019, most municipalities with significantly positive trends in stocking rate had significantly negative or nonsignificant trends in pasture cover in the H-AMP groups. In the L-AMP L-ACI group, 35% of municipalities remained with significantly positive trends in stocking rate and pasture cover in 2012-2019, while the corresponding proportion ranged from up to 4% in H-AMP groups and 18% in L-AMP H-ACI. The proportion of municipalities during 2012-2019 with significantly positive trends in stocking rate but either significantly negative or nonsignificant rends in pasture cover was 26% for H-AMP H-ACI, 24% for both H-AMP L-ACI and L-AMP H-ACI, and 13% for L-AMP L-ACI. Overall, the period of 2012-2019 was that with the greatest proportion of municipalities with significantly positive trends in stocking rate but either nonsignificant or negative trends in pasture cover, reaching 21% of total municipalities.

5 DISCUSSION

5.1 Cattle ranching as a significant driver of deforestation from 2017-2019

This study indicates that cattle ranching persists as a significant driver of recent deforestation (2017-2019) of old-growth forests in the Brazilian Amazon. From 2017 to 2019, 77% of the total area deforested in the study region was converted to pasture. In addition, there was a significant positive relationship between deforestation rates during this period and the proportion of livestock farms across municipalities, which indicates that areas with cattle ranching activity have a high propensity for deforestation. The fact that this relationship was stronger in municipalities with the largest areas of forest available (>3000 km²) also reinforces the pressure that ranching still exerts over old-growth forests as a demand for pasture expansion. This expansion is not only a vehicle for land grabbing and land speculation, but also the mechanism that many ranchers are using to carry their production and participate in the cattle market. Across municipalities of the study region with a predominance of cattle ranching farms, the majority of farms sold animals or produced milk over the 2016-2017 period, and certified private lands had the greatest share of gross total deforested area among the assessed land tenure categories.

Among municipalities with more than 300 km² of old-growth forest area, those in which livestock farms were the vast majority (>75% of farms) had some of the most extreme deforestation rates, but also had a lower median deforestation rate compared to municipalities where livestock farms were expressive but not as predominant (45-75% of farms). Such municipalities in this latter case are mostly present towards the frontier to the interior of Amazon, where ranchers may dispose of larger properties for pasture expansion, while having less competition with other ranchers for land purchasing, land grabbing and land speculation. These advantages may also motivate ranchers from more consolidated areas to migrate into the interior and cause an acceleration of deforestation in these regions by practicing extensive means of production.

Walker et al. (2009) showed that the presence of large cattle herds across municipalities of the agricultural frontier was consolidated from 1990 to 2005, followed by an increase in herd size towards the interior of Amazon. Barona et al. (2010) in addition observed an increase in pasture expansion towards the interior, and together with Nepstad et al. (2006) suggested that many ranches from Mato Grosso state sold their properties to the soy industry and migrated further north where land prices are cheaper. Future research could further address these hypotheses by investigating if there has been a coupled increase in cattle ranching farms and deforestation towards the interior over time. This transition has serious implications because while deforestation in consolidated areas persists, the continuous expansion of cattle ranching to the interior can increase logistical and financial constraints already faced by deforestation control initiatives.

5.2 The contribution of different farming systems to deforestation

Considering the significant positive relationship of cattle ranching and recent deforestation, I developed an index that measures the relative adoption of management practices (AMP) among cattle ranching farms, and another that measures the relative adoption of capital investment (ACI), to understand which farming systems are most contributing to the problem. My findings suggest that the influence of management practices to deforestation was greater than that of capital investment. Municipalities with a lower than average adoption of management practices (L-AMP) concentrated 70% of gross total deforestation from 2017-2019 in the study area. In addition, the intensity of deforestation was on average at least two times higher in municipalities in which their farms had both a lower than average adoption of management practices and capital investment (L-AMP L-ACI), compared to those in the three other farming system groups (H-AMP H-ACI, H-AMP L-ACI, and L-AMP L-ACI). This pattern was also confirmed at the finer scale of census tracts (municipality subdivisions of up to 200 farms each). Deforestation was very incident and widespread among farms of L-AMP L-ACI municipalities considering that 91% of their census tracts had deforested areas from 2017-2019.

Several explanations can be offered for the greater deforestation rates in L-AMP municipalities compared to the H-AMP ones, and especially for the greatest deforestation rates in L-AMP L-ACI municipalities. The proportion of farms that used fertilization and the proportion that used tillage were the main variables driving the AMP index. These two practices are important to sustain pasture productivity, especially in Amazonian regions with a low natural fertility of soils and a high incidence of weed invasion (ARIMA; UHL, 1997, DIAS-FILHO; ANDRADE, 2006; HECHT, 1993). Without proper management, some pastures can be abandoned within ten years after their establishment due to degradation (MATTOS; UHL, 1994; HECHT, 1993). By adopting management practices, field evidence indicates that farmers can improve pasture productivity by 30-490% (ZU ERMGASSEN et al. 2018). In cases where low productivity is a strong motivation for deforestation, the adoption of management practices can therefore reduce farmers' need to expand pasture over forests within their own property, through land purchasing, or through land grabbing. This land sparing effect of management practices has been defended by studies using projections (COHN et al. 2014, GARCIA et al. 2017), and now my findings provided further evidence to this idea based on large-scale observational data.

Furthermore, the proportion of farms with tractors and the value of production were the main variables driving the ACI index, providing an indication about the scale of production and wealth among cattle ranching farms of a municipality. As suggested by Kaimowitz and Angelsen (2008), farmers that invest more capital in their production such as with machinery, specialized labor and increasing herd size, could be shifting their resources away from clearing new forests to focus in their already existing lands. These farmers also have more resources to restore and sustain the quality of their existing pastures. In another large-scale study in the Amazon based on the Agricultural Census of 2006, Souza et al. (2013) also found that municipalities with higher rates of deforestation presented lower levels of income and production value. Although the intensity of deforestation was higher in L-AMP L-ACI municipalities, L-AMP H-ACI municipalities also deserve attention from deforestation command and control as they presented a similar gross total deforestation, in addition to significantly higher deforestation rates than H-AMP municipalities at the census tracts level.

The greater intensity of deforestation in L-AMP L-ACI municipalities, compared to L-AMP H-ACI ones, could be partially explained by the observed lower mean farm area in the former, which suggests that farmers with lower capital investments - and smaller holdings - are using their lands more extensively, probably to compensate for their greater financial and productivity constraints. This corroborates with the suggestion of Fearniside (2005) that deforestation intensity tends to decrease with increases in property size. Mean farm area in H-AMP L-ACI municipalities was as small as that in L-AMP L-ACI municipalities, and the mean old-growth forest area was overall much lower than in all other groups since 2000, with a mean forest cover of about 25% already in the 2004-2008 period. For this group in particular, there is a greater probability that forest scarcity was a precursor factor to the higher adoption of management practices among farms, a hypothesis that was raised by White et al. (2001).

Among the several variables I compared across farming systems, one aspect in which L-AMP municipalities significantly differed from municipalities in all other farming system groups was by having a lower density of slaughterhouses in a 100 km radius. These findings point to a potential positive influence of market accessibility on reducing deforestation in regions with a consolidated cattle ranching economy. In 2009, major meatpacking companies in the Amazon signed “Terms of Adjustment of Conduct” – TAC (also known as the beef moratorium) with the government, agreeing to stop buying cattle from farms with illegal deforestation and not registered in the Rural Environmental Registry (CAR) program. Since then, at least 75% of federally inspected slaughterhouses of the Legal Amazon have signed TAC (ALIX-GARCA; GIBBS, 2017). Gibbs et al. (2016) demonstrated the positive influence of the beef moratorium by showing that the proportion of properties in southern Pará supplying to JBS slaughterhouses and with recent deforestation fell from 36% in 2009 to 4% in 2013.

My findings also point to the beef moratorium’s positive influence because forest loss in L-AMP L-ACI municipalities started to become significantly higher than in H-AMP H-ACI municipalities during the 2008-2012 period. A greater number of farms in this last group, as they are closer to the market, could have therefore stopped deforesting during this period to comply with TAC’s requirements and sustain their sales. Consequently, the adoption of management practices could have increased among farms during this period as a market adaptation strategy that required intensification. This market barrier from the beef moratorium may also be a strong reason why my findings, which were based on a large-scale study area, seem to oppose the idea raised by some studies of an increase in deforestation with a greater adoption of technologies (KAIMOWITZ; ANGELSEN, 2008; VOSTI et al. 2001).

Nonetheless, studies reported the occurrence of deforestation leakages in the beef moratorium system (ALIX-GARCA; GIBBS, 2017, RAJÃO et al. 2020) because companies only monitor their direct suppliers, but indirect suppliers with deforestation can sell their cattle to direct suppliers or engage with them in cattle laundering (GIBBS et al., 2016). Rajão et al. (2020) assessed the cattle supply chain in the states of Pará and Mato Grosso and estimated that around 48% of all slaughtered heads could be contaminated with deforestation from indirect suppliers. As farms in L-AMP municipalities are usually more distant to slaughterhouses and thus receive less pressure from the market, many of them could be likely serving as indirect suppliers to farms in H-AMP municipalities.

Moreover, Wang et al. (2020) demonstrated that since the beef moratorium started, deforestation of secondary forests has been showing an increasing conversion to pasture and have surpassed deforestation of old-growth forests. Future research therefore will be important to evaluate if the patterns observed here for deforestation of old-growth forests among farming systems are similar to those for deforestation of secondary forests.

5.3 Differences in the likelihood of deforestation across land tenure categories

In all farming systems, my findings point that agrarian settlements were the land tenure category with the highest likelihood of deforestation for presenting the greatest differences between its share (%) of total deforested area from 2017-2019 and its share of total old-growth area available in 2016. This greater likelihood is not necessarily analogous to the extent of deforestation, but rather informs deforestation command and control policies where the problem is occurring with more intensity. Certified private lands for example still concentrated the greatest bulk of deforested areas despite their lowest likelihood of deforestation.

Agrarian settlements have been created to support the country's agrarian reform but face in the Amazon many problems arising from poor levels of infrastructure, access to credit, access to the market, technical assistance, and environmental control (ALENCAR et al. 2016). Such constraints stimulate the practice of extensive means of production and the occurrence of land concentration, as many farmers end up selling or renting their lands to wealthier farmers (ALENCAR et al. 2016; CARRERO; FEARNSIDE, 2011, CARRERO et al. 2020, YANAI et al. 2020). Yanai et al. (2020) showed an increase over time in land concentration for an agrarian settlement in the agricultural frontier, which contributed to speed deforestation as they demonstrated that land concentrators tend to deforest more than non-concentrators. All the aforementioned issues revolving agrarian settlements are in line with my observation that municipalities with a lower adoption of management practices (L-AMP) had a greater share of their total deforested area within this land tenure category. This also reveals that ranchers in agrarian settlements should receive priority for public policies aiming to increase the adoption of sustainable production systems, which can motivate their permanence in the settlements rather than moving to new areas.

Undesignated lands and lands not registered in any official database were the subsequent land tenure categories with the highest likelihood of deforestation across farming systems, a consequence of their high vulnerability to land grabbing and land speculation. These two categories had a higher likelihood to be deforested especially in municipalities with a higher adoption of management practices and lower adoption of capital investment (H-AMP L-ACI group). This finding corroborates with the opinion of some studies that investments to increase ranching productivity must be coupled with a strong support of land governance to achieve a land sparing effect, as many ranchers would be willing to further increase their profits to where land is cheap or easily accessible (BOWMAN et al. 2012, GARRETT et al., 2018; KAIMOWITZ; ANGELSEN, 2008; MULLER-HANSEN et al. 2019). The highest likelihood of deforestation for these land tenure categories in H-AMP L-ACI municipalities is likely because our findings also suggest that old-growth forests tend to be scarcer within farms of this farming system group, which can motivate farmers to seek pasture expansion outside of their property limits.

In all farming systems, however, the share of total old-growth forest aea within undesignated public lands or unregistered lands was similarly very low, suggesting that most of the forest area in these tenure categories may had been already intensively grabbed over the consolidation of cattle ranching economy in the study area. The most likely destination of this grabbing process was to the private lands that are currently self-declared by the landowner through the Rural Environmental Registry (CAR) but do not hold legal titling, which is the land tenure category that overall detains the second greatest proportion of old-growth forest area across farming system groups. Azevedo-Ramos et al. (2020) for instance points that 80% of the accumulated deforestation in undesignated public lands in the Amazon occurred in areas that are currently under CAR-only registries.

5.4 Challenges to sustainable cattle ranching intensification in the Amazon

Significant decreases in forest cover were observed for more than 85% of all the analyzed municipalities across the entire period from 2000 to 2019, and despite a gradual decrease in the intensity of forest loss until 2012, all farming system groups experienced a further increase since then. This also reflected in an increase in the proportion of municipalities with significant pasture expansion trends, especially in municipalities composing the farming system group with a lower than average adoption of management practices and capital investment (L-AMP L-ACI). This shift in trends since 2012 mirrors that observed for deforestation in the Brazilian Amazon as a whole, and is in line with the implementation of unfavorable policies to conservation and the weakening of deforestation command and control that has been occurring over this period (see section 2.3; OC, 2021). My findings suggest that L-AMP L-ACI municipalities were the ones that, overall, more negatively responded to the weakening of conservation measures since 2012, and the ones less affected by the several measures to reduce deforestation that occurred from 2004 to 2012 (see section 2.3). The deficiency in these municipalities for effective strategies to reduce deforestation is therefore prevailing and historical, and the assessment of factors that could fill this void is of critical importance.

Despite the increase in municipalities with significant pasture expansion trends from 2012 to 2019, municipalities with such a trend still accounted for less than half of all in each farming system group except for L-AMP L-ACI. Moreover, the magnitude of pasture expansion was consistently reduced over the period from 2000 to 2019 in municipalities with a higher than average adoption of management practices. This implies that while some farms persist with pasture expansion over forests, an expressive portion are reducing their pasturelands. This reduction may be due to forest regrowth in abandoned pasture, and/or a conversion of pasture to other agricultural land uses. Although large scale advancements toward land sparing intensification (increasing stocking rates without pasture expansion at the municipal level) have also been increasing since 2008-2012, they are still low in scope, reaching by 2012-2019 only about 13% of municipalities with a lower adoption of management practices and capital investment, and about 25% of municipalities in each of the other farming system groups.

Land sparing means of intensification could become a more prevalent pattern across Amazonian farms in light of the fact that current stocking rates in the region are much below the estimated carrying capacities (ARANTES et al. 2018; STRASSBURG et al. 2014), and more than half of pasturelands may present some degree of weed invasion (DIAS-FILHO; ANDRADE, 2006). As this study showed that current pasturelands cover on average more than 55% of the land area of cattle ranching municipalities (already excluding protected areas and indigenous lands), many farmers in fact would have to rely on intensification to comply with the legal requirement that legal forest reserves must cover 80% of their properties (or 50% in some cases) (BRASIL, 2012). To guarantee the sustainability of this intensification, one major obstacle to overcome is the very low rates of adoption of management practices such as fertilization and tillage among cattle ranchers in the region.

According to my findings, an expressive portion of farmers from cattle ranching municipalities would benefit from adopting management practices if we consider that, on average, 73% of them are family farmers actively producing, though only 15% received technical assistance. Technical assistance has been positively associated to stocking rate, adoption of fertilization and liming among farmers, as my results suggested, and efforts to expand its reach should be a major concern of policy strategies. Although Brazil's government has a public program of technical assistance for family farmers and most states are providing this service through regional offices, the program receives low funding and cannot meet the demand of all family farmers (CASTRO; PEREIRA, 2017). Paula Filho et al. (2016) for example pointed that regional offices of technical assistance could only meet 10% of farmers' demand in the Amazonian municipalities they analyzed.

Another challenge faced by farmers refer to the costs that transitioning to sustainable intensification requires, which may vary from US$410-2180/ha with a payback in 1.5-12 years (ZU ERMGASSEN et al., 2018). Latawiec et al. (2017) surveyed 250 Amazonian ranchers and 34% of them reported high costs as a main limitation to adopt management practices. Increasing market accessibility could be an important step to boost this adoption, considering that farming inputs can be very expensive due to the long distances for transportation and bad road conditions (CASTRO, 2013). Morello et al. (2018) for example found that market proximity was the most relevant factor determining Amazonian farmers' decision to utilize fertilizers. Here I found that the adoption of fertilization and liming was positively associated with the density of slaughterhouses, which may in part be a result of the better opportunities offered by more dynamic markets.

Credit is a key mechanism to enable farmers to cover the costs from sustainable intensification, and my correlation analysis highlighted that its greater diffusion among farms is associated with less pasture degradation and greater stocking rates. Lines of rural credit however lack scope in the Amazon. Some studies for example reported that the North region (which encompasses most Amazonian municipalities of Brazil) has been sharing less than 5% of the country’s funds of credit over the years (LEITE; JUNIOR, 2015; ARAUJO; LI, 2018). One promising line of credit to assist in cattle ranching intensification comes from the government’s Low Carbon Agriculture Program (ABC), which is designed to promote carbon mitigation measures such as pasture restoration and integrated crop-livestock-forest systems. Since the beginning of the ABC Program’s implementation in 2011 until 2019, the relative amount of the program’s annual funds hired by the North region increased from 8% to 21.5% (OBSERVATORIO ABC, 2019). Technical surveys in Amazonian municipalities reported that some of the main challenges to increase the scope of ABC Program in the region are the lack of secure land rights for many farmers, the low availability of public technical assistance, and the low dissemination of the program from banks to farmers (OBSERVATORIO ABC, 2015, OBSERVATORIO ABC, 2019).

6 CONCLUSION

With the use of large-scale observational data, this study provided supporting evidence for the land sparing potential of adopting management practices for cattle ranching production in the Brazilian Legal Amazon. For municipalities where cattle ranching is the leading production activity, 70% of the total deforested area from 2017 to 2019 was within municipalities where the adoption of management practices among farms was lower than average. Moreover, deforestation rates during this period were greatest in municipalities with a lower than average adoption of both management practices and capital investment. In fact, trends in forest loss were significantly greater for these last municipalities since the 2004-2008 period compared to municipalities with a higher adoption of management practices but a lower adoption of capital investment, and since the 2008-2012 period compared to municipalities with both a higher adoption of management practices and capital investment. The magnitude of pasture expansion consistently decreased from 2000 to 2019 in municipalities with a higher adoption of management practices, and more than 60% of these municipalities did not have significant increases in pasture expansion during the 2012-2019 period. The proportion of municipalities with significant increases in stocking rate without significant increases in pasture cover started to rise since the 2008-2012 period, but still accounted for only 21% of all analyzed municipalities during the 2012-2019 period.

My findings indicate that policies aiming to prevent deforestation in the municipalities studied here could consider increasing the adoption of management practices among cattle ranchers as one of the major strategies. This would require an amplification of investments in market accessibility, technical assistance, and access to credit. In addition, ranchers in agrarian settlements should receive priority from policy interventions, as this land tenure category had the highest likelihood of deforestation and face many socioeconomic constraints.

It is important to stress, however, that all this evidence were drawn from regions of the agriculture frontier with a consolidated cattle ranching economy. There is a minimal relative amount of undesignated public forests left in these municipalities. The same large-scale land sparing effect found here may not necessarily hold true for Amazonian regions located more into the interior, where cattle ranching is less predominant and there is a greater abundance of undesignated public forests for grabbing. Thus, the diffusion of cattle ranching intensification across the Amazon will need a strong support of land governance, with the proper designation of undesignated public lands. A reinforcement in deforestation command and control is also critical to sustain the land-sparing potential of production measures in the consolidated cattle ranching regions. According to my findings, the magnitude of forest loss increased from 2008-2012 to 2012-2019 in municipalities from all the analyzed farming systems, which is in line with the implementation of policies unfavorable to conservation and the weakening of deforestation command and control that has been occurring since 2012.

Cattle ranching has been a major agricultural activity in the Amazon and as demonstrated here, the proportion of cattle ranching farms in municipalities was significantly positively associated with recent deforestation rates. For a plan of sustainable agricultural development in the region, this highlights the importance of increasing the participation of less land-demanding agricultural activities by making them more economically attractive for farmers.

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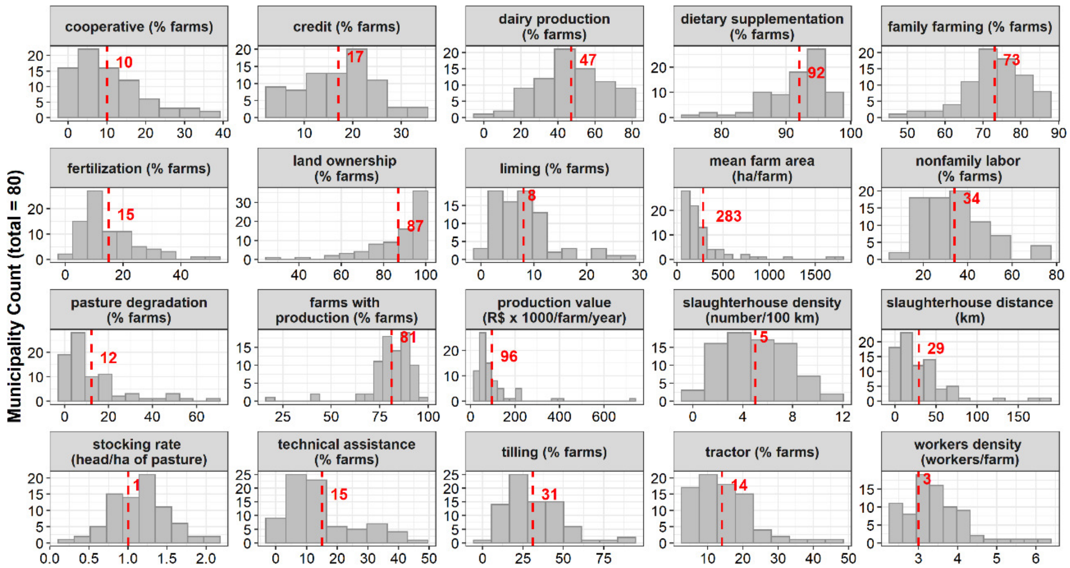
APPENDIX A – SUPPLEMENTARY FIGURES AND TABLES

A.1 Figures

Figure A.1. Histogram of cattle ranching variables for municipalities in the Cattle Ranching Zone.



Detailed information about the variables can be found in Table 3.1. Red dashed lines represent the mean value of each variable across municipalities.

Source: Produced by this author.

A.2 Tables

Table A.1. Comparison of cattle ranching statistics across municipalities divided into four farming system groups. H and L stand respectively for higher and lower. AMP stands for Adoption of Management Practices and ACI stands for Adoption of Capital Investment.

Variable	H-AM H-ACI	H-AMP L-ACI	L-AMP H-ACI	L-AMP L-ACI
cooperative (%)	10^{a}	10^{a}	9^{a}	11^{a}
credit (%)	18^{a}	16^{a}	17^{a}	17^{a}
dairy production (%)	41^{a}	53^{b}	47^{ab}	48^{ab}
dietary supplementation (%)	92^{a}	90^{a}	92^{a}	91^{a}
family farming (%)	70^{a}	74^{ab}	70^{a}	77^{b}
fertilization (%)	24^{a}	18^{a}	9^{b}	8^{b}
land ownership (%)	91^{ab}	81^{a}	91^{b}	84^{a}
liming (%)	12^{a}	9^{a}	5^{b}	5^{b}
mean farm area (ha/farm)	383.71^{a}	183.29^{b}	442.48^{a}	138.36^{b}
nonfamily labor (%)	37^{a}	28^{a}	41^{b}	30^{a}
pasture degradation (%)	10^{a}	13^{a}	13^{a}	14^{a}
production (%)	79^{a}	82^{a}	78^{a}	84^{a}
production value (x R$ 1000/farm/year)	150.67^{a}	66.08^{b}	117.98^{a}	43.46^{c}
slaughterhouse density (slaughterhouses/100 km)	5^{a}	5^{a}	6^{a}	3^{b}
slaughterhouse distance (km)	20^{a}	25^{a}	29^{ab}	42^{b}
stocking rate (head of cattle/ha)	1.22^{a}	1.2^{a}	1.13^{a}	1.07^{a}
technical assistance (%)	20^{a}	15^{ab}	14^{a}	9^{b}
tillage (%)	43^{a}	42^{a}	20^{b}	19^{b}
tractor (%)	23^{a}	11^{b}	15^{c}	8^{d}
workers density (workers/farm)	3.6^{ab}	3.2^{a}	3.7^{b}	3.4^{ab}
annual deforestation rate	0.77^{a}	0.64^{a}	0.85^{a}	2.43^{b}
deforested area from 2017-2019 (km²)	58.16^{ab}	39.57^{a}	127.7^{b}	118.75^{b}
old-growth forest area in 2016 (km²)	2558.05^{a}	1537.58^{b}	3267.95^{a}	1791.52^{a}

Values for all variables represent the mean in each group, except for annual deforestation rate from which values represent the median. Letters indicates whether there is a statistically significant difference at the 5% level across groups.

Source: Produced by this author.

Table A.2. Proportion of municipalities in each farming system group with significant and no significant trends in the time-series of old-growth forest cover (%), pasture cover (%), and stocking rate (heads of cattle/ha).

Time interval	Variable	Farming system	no signif.	signif. neg.	signif. pos.	signif. pos. x signif. pos.	signif. pos. x signif. neg.	signif. pos. x no signif.
2000-2004	old-growth forest cover	H-AMP H-ACI	0	100%				
		H-AMP L-ACI	0	100%				
		L-AMP H-ACI	0	100%				
		L-AMP L-ACI	0	100%				
	pasture cover	H-AMP H-ACI	35%	0	65%			
		H-AMP L-ACI	41%	0	59%			
		L-AMP H-ACI	29%	0	71%			
		L-AMP L-ACI	35%	0	65%			
	stocking rate	H-AMP H-ACI	83%	0	17%			
		H-AMP L-ACI	70%	6%	24%			
		L-AMP H-ACI	75%	0	25%			
		L-AMP L-ACI	71%	0	29%			
	stocking rate x pasture cover	H-AMP H-ACI				17%	0	0
		H-AMP L-ACI				24%	0	0
		L-AMP H-ACI				19%	0	6%
		L-AMP L-ACI				24%	0	5%
2004-2008	old-growth forest cover	H-AMP H-ACI	0	100%				
		H-AMP L-ACI	0	100%				
		L-AMP H-ACI	0	100%				
		L-AMP L-ACI	4%	96%				
	pasture cover	H-AMP H-ACI	48%	0	52%			
		H-AMP L-ACI	65%	6%	29%			
		L-AMP H-ACI	35%	0	65%			
		L-AMP L-ACI	31%	4%	65%			
	stocking rate	H-AMP H-ACI	79%	17%	4%			
		H-AMP L-ACI	94%	6%	0			
		L-AMP H-ACI	82%	18%	0			
		L-AMP L-ACI	70%	4%	26%			
	stocking rate x pasture cover	H-AMP H-ACI				4%	0	0
		H-AMP L-ACI				0	0	0
		L-AMP H-ACI				0	0	0
		L-AMP L-ACI				22%	0	4%
2008-2012	old-growth forest cover	H-AMP H-ACI	13%	87%				
		H-AMP L-ACI	12%	88%				
		L-AMP H-ACI	0	100%				
		L-AMP L-ACI	4%	96%				
	pasture cover	H-AMP H-ACI	70%	0	30%			
		H-AMP L-ACI	88%	6%	6%			
		L-AMP H-ACI	59%	6%	35%			
		L-AMP L-ACI	57%	4%	39%			
	stocking rate	H-AMP H-ACI	87%	0	13%			
		H-AMP L-ACI	71%	0	29%			
		L-AMP H-ACI	65%	0	35%			
		L-AMP L-ACI	70%	4%	26%			
	stocking rate x pasture cover	H-AMP H-ACI				4%	0	9%
		H-AMP L-ACI				6%	0	24%
		L-AMP H-ACI				18%	6%	12%
		L-AMP L-ACI				17%	0	9%
2012-2019	old-growth forest cover	H-AMP H-ACI	4%	96%				
		H-AMP L-ACI	0	100%				
		L-AMP H-ACI	0	100%				
		L-AMP L-ACI	4%	96%				
	pasture cover	H-AMP H-ACI	39%	26%	35%			
		H-AMP L-ACI	47%	24%	29%			
		L-AMP H-ACI	53%	6%	41%			
		L-AMP L-ACI	26%		74%			
	stocking rate	H-AMP H-ACI	70%	0	30%			
		H-AMP L-ACI	76%	0	24%			
		L-AMP H-ACI	47%	12%	41%			
		L-AMP L-ACI	48%	4%	48%			
	stocking rate x pasture cover	H-AMP H-ACI				4%	13%	13%
		H-AMP L-ACI				0	0	24%
		L-AMP H-ACI				18%	0	24%
		L-AMP L-ACI				35%	0	13%

Trends were calculated with the Mann-Kendall test at the 5% level of significance. H and L stand respectively for higher and lower. AMP stands for Adoption of Management Practices, and ACI stands for Adoption of Capital Investment.

Source: Produced by this author.