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Impact of environmental law enforcement on deforestation, land use and natural regeneration in the Brazilian Amazon

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September 2019

This thesis is submitted for the degree of Doctor of Philosophy

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Summary

Humankind is facing one of the most challenging periods in its short history on Planet Earth. These challenges have largely arisen as a result of climate change and the loss of tropical forests. Indeed, these challenges present two of the greatest environmental challenges of all time. Nevertheless, Brazil has recently adopted policies that have greatly reduced forest loss over the past decade or more. A strong combination of different policies and actors have made this achievement possible, and environmental law enforcement is thought to have played a key role. Therefore, the central questions for this thesis is to determine the influence of environmental law enforcement, mostly ground operations in the Brazilian Amazon region, on reducing deforestation, reshaping land use change, through livestock, agriculture and natural restoration, and the persistence of natural regeneration. First, I assess the influence of law enforcement on forest loss reduction through a spatial analysis at the municipality level. The results confirmed that law enforcement, along with other factors, is an important influence on reducing forest loss. However, law enforcement also has to tackle some administrative limitations, as a shift and modernization of the environmental police strategy is imperative to face the new challenges, and the appropriate implementation of the rural environmental registry policy will be crucial. Second, I explore the possible influence of law enforcement on reshaping land use change, focusing on annual crops, livestock and natural regeneration, using a difference-in-differences with an entropy balance approach at the municipality, private property and settlement levels. I have evaluated the priority municipality policy implemented in 2008 that led to an intensification of law enforcement on target municipalities. The results show an increased persistence of agriculture and clean pastures, as a substantial increase in natural regeneration occurs through abandonment, a reduction of dirty pastures, and suggests an influence of law enforcement on this land use dynamic. Annual crops, mostly soy, turned to be an agglomerated economy in the central area of Mato Grosso, while extensive pastures are more widespread with low levels of occupation and also as part of land speculation. Both activities are showing signs of intensification and land sparing, at least for natural regeneration. So, conservation policies based on law enforcement have contributed to the reshaping of land use systems in the Brazilian Amazon. Although certainly not alone, but in combination with other policies and initiatives. This study shows that law enforcement became a stronger component of farmers' land use

investments and decision-making processes. Thus, while pockets of illegality still prevail, environmental and land tenure law enforcement will be mandatory. Only with this will it be possible to ensure the effectiveness of a sustainable intensification, reduction in forest loss, and fulfil the role of spare lands for conservation, agriculture and ultimately achieve a balanced land use system. Third, I present results of the possible influence of law enforcement on the persistence of over 41,000 km2 of natural regeneration during the past 10 years of this study. This question has received much less attention than the others, and it is not clear what is driving this persistence of regeneration. Therefore, this thesis sought to investigate if this persistence could be a co-benefit of the environmental police actions against deforestation. The results suggest a positive effect of command and control on the persistence of natural regeneration. This observation has important implications for the Brazilian climate change policies and restoration commitments under the Paris Agreement. Furthermore, it could represent a substantial contribution to the global restoration targets established at CBD, Bonn Challenge and New York Declaration on Forests. I conclude where I started, with the conviction that is possible to balance conservation and production. The results of this thesis are encouraging and suggest the strong influence of law enforcement, as catalyst, on reshaping land use system dynamics towards intensification, forest loss reduction and increased natural regeneration persistence in the Brazilian Amazon region. However, it is also clear that this can be an unstable balance and any political and/or policy perturbations may cause big losses and quickly reverse the consistent advances seen during study period. So, the challenge ahead is to make this balance consistent and stable, and less vulnerable to perturbations.

Dedication

For Lu and Isadora, my queen and princess, my reason for living, my family!

Isadora, my source of inspiration to think of a better world
so she can live her adventures intensely, as her parents lived.

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I owe a huge debt of gratitude to the many people who helped make my dream come true. It has been a long, reflective and lonely journey to reach the completion of this piece of work. I am sure I have done my best and listened carefully to all the contributions and critiques to incorporate in what you are just about to read, although nobody is to blame for its faults but me.

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List of Acronyms

ABIOVE – Brazilian Association of Vegetable Oil Industries

AFOLU - Agriculture, Forests and Other Land Uses

AMBDATA - Environmental dataset for modelling species distribution

APA - Environmental Protection Areas

APP - Permanent Preservation Areas

BACEN – Brazilian Central Bank

CAR – Rural environmental registry

CBD - Convention on Biological Diversity

CEPEA - Centre for advanced studies in applied economics

CONAB - National Supply Company

COP - Conference of the Parties

CPATU/EMBRAPA - Tropical Agricultural Research Center/EMBRAPA

CPTIA/EMBRAPA - Agricultural Informatics/EMBRAPA

CRA – Amazon Regional Center/INPE

DETER – Early warning of alteration on forest cover in the Amazon

EMBRAPA - Brazilian Agricultural Research Corporation

FUNAI - Indigenous people National Foundation

GDP - Gross Domestic Product

GEF - Global Environment Facility

GHG – Greenhouse Gas

GTPS - Workgroup on Sustainable Livestock Production

Ibama – Brazilian Institute of Environment and Renewable Natural Resources

IBGE - Brazilian Institute of Geography and Statistics

ICMBio - Chico Mendes Institute for Biodiversity Conservation

IGPM - General Market Price Index

INCRA - National Institute for Colonization and Agrarian Reform

INPE – National Institute for Space Research

IPCC - The Intergovernmental Panel on Climate Change

IPEA - Institute of Applied Economic Research

LR - Legal Reserve

MAPA - Ministry of Agriculture, Livestock, and Supply

MCTIC - Ministry of Science, Technology, Innovation and Communication

MDIC - Ministry of Development, Industry and Foreign Trade

MMA - Ministry of the Environment

NDC – National Determined Contributions

PA – Protected Areas

PAM/IBGE – Municipal Agricultural Production/IBGE

PNMC - National Climate Change Policy

PPCDAm - Action Plan for the Prevention and Control of Deforestation in the Legal Amazon

PPM/IBGE – Municipal Livestock Production/IBGE

PRA - Environmental Regularization Program

PRODES - Brazilian Amazon Rainforest Deforestation Monitoring by Satellite

PRONAF - Family Farming Strengthening Program

REDD+ - Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries

SCDB - Secretariat of the Convention on Biological Diversity

SDG – Sustainable Development Goals

SFB – Brazilian Forest Service

SICAFI - Registration, Collection and Inspection System

SICAR – National System for Rural Environmental Registry

TERRACLASS – Land use and land cover mapping program

UN – United Nations

UNCED - United Nations Conference on Environment and Development

UNFCCC - United Nations Framework Convention on Climate Change

1. Introduction

The Anthropocene era is now upon us, and 'there is no wild nature that stands outside human impact' (Braun, 2015 p.107). Humankind needs both a low carbon economy, as well as development. The dual challenge is how to trade off all land uses as virtuous solutions for conservation, food security and bioenergy. In the midst of this complexity, tropical forest loss is one of the greatest global challenges for humankind. Brazil is at the centre of this challenge. On the one hand, Brazil has achieved incredible reductions in forest loss over 12 years (2004-2016). On the other hand, Brazil is still considered to be one of the largest deforesters globally.

Sections 1.1 to 1.4 will situate Brazilian deforestation in the context of climate change mitigation, more specifically in the Agriculture, Forests and Other Land Uses (AFOLU) framework. This is a complex set of interrelated challenges with direct impacts on human lives and livelihoods. The section will then move more specifically to the Amazon region to review the intricate patterns of deforestation[1] witnessed during the last few decades, highlighting the role of environmental law enforcement and of the land use dynamics of agriculture, livestock and natural regeneration. The section will close by offering an integrated approach to the topics discussed previously. The specific questions and hypotheses of the study will be introduced along this section and summarized at the end, closing with the outline of the thesis chapters.

1.1 Climate change

Humankind is facing one of the most challenging periods in its short history on Planet Earth, in large part as a result of climate change. The Earth's climate has always fluctuated across its surface 'from intervals of many years to many millennia in duration' (Karl and Treberth, 2005 p.15). Meanwhile, temperature has also varied substantially over the last 800,000 years (McManus, 2004). Human influence on climate change became pervasive and prominent during the industrial revolution, with the increasing use of fossil fuels in Europe and the growing influence of land use change through agriculture and deforestation globally (IPCC, 2014a; IPCC, 2019).

As a result, human influence on the Earth's climate system has led to atmospheric and ocean warming, while snow cover and ice has decreased, and sea levels have risen. Wild Nature too has been negatively affected: extinctions now occur at rates never seen previously, due to massive

[1] Here deforestation is defined as the total removal of forest cover.

habitat loss and fragmentation (Burkey, 1989; Andrén, 1994; Burkey, 1995; Laurance and Bierregaard, 1997; Pearson and Dawson, 2003; Opdam and Wascher, 2004; Hannah et al., 2005; Thuiller et al., 2005; Araújo et al., 2006; Vos et al., 2008; Sieck et al., 2011). Species distributions are changing, and migrating towards higher altitudes and lower latitudes, accompanied by changing breeding seasons, phenology, morphology, physiology and behaviour (SCBD, 2010a). In the future, food security will be increasingly termed 'food insecurity'. Once productive areas will be displaced and crop yields will drop due to changes in climatic conditions. Energy use based on use of fossil fuels will be by far the largest threat to Planet Earth.

Climate change is getting worse, and the last 30 years were the warmest ever registered (IPCC, 2014b). In 2010, anthropogenic emissions reached 49 $GtCO_2eq$/year, 65% from fossil fuels and 24% (~10–12 $GtCO_2eq$/year) from agriculture, forest and other land use (AFOLU) (IPCC, 2014a; Smith et al., 2014). This raises the fundamental question of whether human kind is running straight and fast over the cliff. The answer is probably in the affirmative. However, the opportunity still remains to stop and contemplate the view, rather than to jump. Or is this scenario already too optimistic? The answer is again probably in the affirmative. However, there is some evidence to suggest humankind can take the actions necessary to mitigate, and adapt to, climate change if it acts quickly (IPCC, 2014b; Smith et al., 2014).

The Paris Agreement was signed at the 21st Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC), and ratified by 177 Parties in May 2016, which is a good sign. Planet Earth needs both a low carbon economy, as well as development. Closely related to the Paris Agreement is the 17 Sustainable Development Goals, another agreement pointing in the same direction of a more sustainable planet (UN, 2015).

More positively, and in contrast to the global upward trend seen in GHG emissions, Brazil reduced its emissions by more than 50% during 2005-2010 (Brazil, 2016), based on policies and actions that consistently reversed deforestation in the Brazilian Amazon. Despite the different trends seen globally and in Brazil, CO_2 emissions from tropical forests have declined in both cases. Globally, this decline has been due to the reduction in deforestation, influenced by Brazil's results, and afforestation, most notably in China, Vietnam and India (Rudel et al., 2005; FAO, 2014).

Even though the substitution of fossil fuel by biomass energy is crucial to mitigate climate change, the actual global average of renewable energy is only 14%, compared with 48% in Brazil. Given this scenario, it is imperative that all nations explore and adopt renewable energy sources, such as wind, solar, biomass, bioenergy and hydro-power energy. Furthermore, all nations should take the necessary precautions to avoid the replacement of natural areas or competition with food production. Sequestration of carbon by afforestation and reforestation can have positive impacts on GHG emissions and biodiversity, particularly if implemented with native species and in degraded lands.

The actual share of annual GHG emissions in Brazil during 2000–2010 was 5.0–5.8 $GtCO_2eq$/year for agricultural production and approximately 4.3–5.5 $GtCO_2eq$/year from land use and land-use change activities. This was equivalent to 10-12% and 9-11% of total GHG emissions, respectively (Smith et al. 2014).

Since the 1970s', global agricultural production has increased by 7% of the world's land area. This is not good for conservation, because it relies on the conversion of natural areas, especially in developing countries (Queiroz et al., 2014; Mullan et al., 2017). Equally, the situation could have been far worse if this period in history had not been accompanied by so many technological advances. For instance, the world grain harvest and cereal yield doubled in 2010 to 2.5 billion tonnes and 3030 kg/ha, respectively. However, this increase came with a price. The use of inorganic fertilizers has increased by 800% since the 1960s' (IPCC, 2019), land degradation has occurred through soil erosion, inappropriate irrigation and poor land management practices (Dobermann et al., 2013). Meanwhile, GHG emissions have increased 9-fold during the last 50 years (Tubiello et al., 2013). In addition, livestock emissions, mainly through enteric fermentation, rose by 50% in the last 50 years (Dobermann et al., 2013).

Conservationists are rightly concerned. Even with the increased coverage of Protected areas (PAs) during the last decade, from 12 to 14% of terrestrial lands, Aichi Biodiversity Target 11 (SCBD, 2010b) to protect 17% of terrestrial and inland water, and 10% of coastal and marine areas, is far from being achieved. This is because PAs are not evenly distributed across the priority natural areas around the globe. Moreover, many priority areas are threatened by other land uses, mostly agriculture and livestock. At the same time, agricultural land globally has decreased by 53 Mha since 2000' (Smith et al., 2014 p.822). However, in 2014, the Brazilian Amazon supported 17.3 Mha of deforested areas up to 2004 that were recovering naturally (Inpe, 2016b). Encouragingly, these last figures contribute to meet Aichi Target 15 - to enhance carbon stocks through restoration of at least 15% of degraded ecosystems (SCBD, 2010b).

An important sign that it is possible to change human influence on nature comes from Chapter 11 of the IPCC 2014 Report on AFOLU (Smith et al., 2014) and the IPCC Climate change and land report

(IPCC, 2019). Here, the authors point out emerging issues that have the potential to reverse emissions, including:

- `consumption patterns, through dietary change;
- production patterns, through large scale acquisitions in lower-income countries;
- production and consumption patterns, through switching to low carbon products;
- relations between producers and consumers, through certifications schemes; and,
- management priorities, through increasing interest in conservation and sustainable land management) (Smith et al., 2014 p. 844).

These emerging issues must be accompanied by strong political will to act for the common good. In order to be successful, collective actions should consider social, economic and environmental factors, at multiple levels, that will have important roles in solving these common problems (Berkes, 2007; Ostrom, 2007). Such problems will vary significantly across space and time, and across scales of intervention. Consequently, there is no one solution that fits all. Indeed, there is no panacea[2], and some scholars have observed that there is no single solution for all the complex situations at the conservation-development interface (Dietz et al., 2003; Berkes, 2004; Child, 2004). In fact, each case needs to be analysed individually and within its own context, taking into consideration these social, economic and political factors (Berkes, 2007; Nagendra, 2007; Ostrom et al., 2007).

The previous paragraphs have outlined some of the complexities of mitigating climate change for AFOLU. These complexities generate heated debate among specialists, scholars, practitioners and policy makers. There are gaps in knowledge that limit more detailed analyses and model projections, also due context-specific nature of each case. The challenge is how to balance all land uses as virtuous solutions for conservation, food security and bioenergy. In others words, to achieve the sustainable development and the UN 17 SDGs goals.

The following section will introduce Brazil's efforts to reverse Amazon deforestation during the last 15 years. So far, Brazil has been considered to be one of the most successful mitigation initiatives globally (Tollefson, 2012; Nepstad et al., 2014; Tollefson, 2015). It is still a work in progress, with the recent start of PPCDAm's 4th phase in 2016. There have been three independent evaluations in-between, to adjust directions and targets. This has been complemented by a large volume of

[2] The Oxford English Dictionary defines panacea as "…a remedy, cure, or medicine reputed to heal all diseases; a universal remedy." Here, according to Ostrom and colleagues (2007 p.15176): 'panaceas are the action or tendency to apply a single solution to many problems. In the governance of human–environment interactions, a panacea refers to recommendations that a single governance system blueprint (e.g., government ownership, privatization, community property) should be applied to all environmental problems.'."

research produced by the scientific community in trying to understand the circumstances that led Brazil to these remarkable mitigation results, but also pointing out gaps and offering incentives for Brazil to continue on its path.

Therefore, gaining a better understanding of the complex chain of policies and actions that have contributed to reversing deforestation in Brazil should prove a great contribution for future mitigation of forest loss around the globe. Indeed, the results from this study could be used and adapted to deforestation in other local or regional contexts.

1.2 Amazon Deforestation: PPCDAm and Law enforcement

The control of tropical forest loss presents one of the greatest environmental challenges of our time (Fearnside, 1983; Hecht, 1985; Hecht, 1989; Hecht, 1993a; Moran, 1993; Nepstad, 1997; Angelsen and Kaimowitz, 1999; Barbier et al., 2001; Soares-Filho et al., 2004; Fearnside, 2005; Soares-Filho et al., 2005; Kirby et al., 2006; Soares-Filho et al., 2006; Brondizio and Moran, 2008; Nepstad et al., 2009; Taitson, 2011; IPCC, 2014a; De Souza and De Marco, 2015). For instance, Brazil and Indonesia have accounted for 60.6% of worldwide loss of tropical forests between 2000 and 2005 (Rudel et al., 2009a).

Nevertheless, Brazil has reduced Amazon deforestation by 76% during the last 13 years (Inpe, 2017). This achievement has sparked interest from different areas of the scientific community who wish to understand this phenomenon from environmental, economic and social perspectives, following the three pillars of sustainable development (WCED, 1987). Moreover, “maintaining carbon stocks in tropical forests is widely recognized as a relatively low-cost option for mitigating climate change” (DeFries et al., 2010 p.178).

Amazon deforestation and land use started long before the arrival of the Portuguese in 1500. Various lines of evidence suggest that human activities have impacted at least 390,000 km^2 of forests (9%), in the most conservative study (Balée, 1989). Meanwhile, Denevan (1992) estimated that 40% of Latin America tropical forests were in some stage of secondary succession. Magalhães (2008) goes further and suggests that 60% of Amazon forests were somehow managed. Nevertheless, this is not comparable to the intensity of transformations that have occurred in the last 50 years in the Amazon region, in which a total of 768,000 km^2 (15%) has been clear cut (Inpe, 2017). The last half century has seen an acceleration in the rate of Amazon deforestation that can be briefly explained in three periods: military (1964-86), early democracy (1987-2003) and PPCDAm[3]/ PNMC[4] (2004-2018).

The military coup in 1964 initiated a period in the Amazon region that was marked by a political and economic vision of integration and occupation of the territory, tax incentives, favouring a business elite from the southeast, livestock expansion and high inflation. Later, following rural social pressures in other regions, the government started a more social approach, implementing public and private colonization projects (settlements), with the slogan: 'Amazon: the land without people for landless people' (Moran, 1981; Hecht, 1985; Oliveira, 1997; Lui, 2013). Thus, a network of highways was built, as a crucial part of the strategy to provide access to resources, and to integrate and secure national borders (Dalla-Nora et al., 2014; Arima et al., 2015).

These policies were heavily criticized in the literature: 'disastrous policies' and 'perpetuating deleterious social and environmental policies' (Bryant, 1992 p.15). Besides being ineffective, these policies were economically unfeasible and environmentally unfriendly, lacking as they did, any kind of political control (Moran, 1981; Fearnside, 1983; Mahar, 1988; Frohn et al., 1990; Hecht, 1993a; Hecht, 1993b; Moran, 1993; Moran et al., 1994; Dale et al., 1994. ; Nepstad, 1997; Oliveira, 1997; Bryant, 1999).

The next period (1987-2003) was marked by the rebirth of democracy in Brazil, the enactment of the new Constitution (Brazil, 1988), economic stabilization in the country, inflation control, the permanent expansion of agriculture and livestock into the Amazon region, the beginning of the globalization of the economy and a significant rise in environment awareness.

This period was characterized by the influence of the international economy over Amazon forest loss, which rose and fell in harmony. In contrast, national and international environmental and human rights organizations were heavily pressuring the government to halt deforestation and rural violence in the Amazon. In 1988, just after the new Constitution was adopted, the government launched the first policy plan to reverse and confront violence, and the alarming rates of deforestation, called "*Nossa Natureza"* (Our Nature). This marked the creation of Prodes, the Brazilian Amazon rainforests satellite monitoring program, run by Inpe[5], and the end of the incentives from the previous period. However, only two months after the launch of the plan, Chico Mendes, a notorious rubber tapper, who was fighting for the creation of a sustainable reserve to explore rubber, was brutally killed by

[3] Plan to prevent and control deforestation in the Amazon
[4] National Climate Change Policy
[5] National Institute for Space Research

ranchers. In 1989, as a response to social pressures, the government created the Brazilian Environment Agency (Ibama).

In 1992, Brazil hosted the United Nations Conference on Environment and Development (UNCED), also known as the ‘Rio de Janeiro Earth Summit.’ This environmental conference was marked by the creation of the three conventions for: climate, biodiversity and desertification. The conference also adopted the Declaration on forests principles and encouraged the global spread of environmental awareness.

None of these interventions or events, however, could halt the ‘tsunami’ of Amazon deforestation that started in the military period. In addition, Brazil was entering the globalized economy as a major supplier of commodities, including soy, meat and iron. Plenty of areas were available in the new frontier of the Amazon. A big ‘boom’ in production of soy and livestock took place in the Brazilian agricultural sector. Therefore, through inertia, patterns of Amazon deforestation rose and fell in line with the global economy. A feeling of helplessness took hold, leaving an open question: ‘Can deforestation in the Amazon be stopped (Fearnside, 1983; Bryant and Bailey, 1997; Uhl et al., 1997; Angelsen and Kaimowitz, 1999; Barbier et al., 2001; Laurance et al., 2002; Fearnside, 2005; Kirby et al., 2006; Taitson, 2011)?

The third period (2004-2018) marked the ascent to power of the workers’ party, the continuity of the economic policy, controlled inflation, poverty and social inequality reduction, robust expansion of agriculture and livestock and consistent reduction of Amazon deforestation. In this period Brazil become an important global player in agriculture and environment, and the period was marked by the release of two important national policies: PPCDAm (Brazil, 2004) and PNMC (Brazil, 2009) among others.

The period started in 2004 when annual rates deforestation stood at 27,772km^2, the second highest ever recorded in the Brazilian Amazon since the monitoring programme began in 1988. Moreover, the IPCC reports (I to IV) and the United Nations climate change conferences (UNFCCC) were raising awareness’ of climate change trends towards important tipping points, and claiming for action.

In order to deal with deforestation in the Brazilian Amazon, the new government decided to take action in 2004, but followed a different approach. The President created a permanent inter-ministerial working group to combat deforestation, coordinated by the Chief of Staff, and involving 13 ministries. The President sent a clear and direct message on how to deal with the complex process of Amazon deforestation, by adopting a landscape perspective and pursuing a sustainable development policy for the Amazon, that balanced conservation (protection) and development (production).

A plan emerged from this working group in 2004. So far, PPCDAm had achieved remarkable results by implementing a full range of innovative policies and measures to improve governance and transparency. These include:

- improvements in law enforcement;
- fines and embargoes imposed on those associated with illegal deforestation;
- cuts in rural credit for illegal deforesters;
- publication of the priority municipalities list for monitoring and control;
- robust improvements in the satellite monitoring systems;
- creation of new protected areas;
- recognition of Indigenous lands;
- allocation of federal public lands (Terra Legal Programme);
- multi sectoral agreements: soy moratorium[6] and the workgroup on sustainable beef production (GTPS);
- among others.

As a result, some researchers suggested that decreases in the price of commodities in international markets, and the resulting increase of public awareness, have also contributed to the slowing of deforestation in the Amazon (Barreto et al., 2008; De Souza et al., 2013; Boucher et al., 2014; Nepstad et al., 2014).

Next, the Brazilian Climate Change Policy (PNMC) was established in 2009 (Law 12,187). In Copenhagen, amid an otherwise generally disastrous international negotiation, Brazil formalized an ambitious voluntary commitment to reduce its projected GHG emissions between 36.1 and 38.9% by 2020, compared to business as usual (Brazil, 2009). Furthermore, the goal for the Amazon was to cut deforestation by 80% by 2020. This policy has already produced bold results. For instance, Brazilian emissions have been reduced by 41%, equivalent to 650 million tons of CO2eq/year, mostly by the

[6] The soy moratorium was agreed in 2006 between Greenpeace and ABIOVE, civil society and soy buyers respectively. The signed agreement says that the big buyers would not fund, buy and/or sell soybean from areas that were deforested after July 2006.

76% decline in Amazon deforestation since the implementation of the Plan to Prevent and Control Deforestation in the Brazilian Amazon (PPCDAm)[7] in 2004 (Inpe, 2015).

By 2010, Brazil was considered the third major exporter of agricultural commodities. At the same time, the cuts in Amazon deforestation made Brazil a global leader in climate change mitigation (Tollefson, 2012; Tollefson, 2015). So far, Brazil had done more to reduce emissions than any other country in the world in recent years (Boucher et al., 2014), despite remaining one of the largest deforesters of rainforests of the world (Hansen et al., 2013). In contrast to the previous period, deforestation was clearly declining, while the economy was increasing (Barretto et al., 2013; Nepstad et al., 2014), despite the 2009 global crises, which almost did not hit Brazil. However, deforestation in the Brazilian Amazon has stabilized at around 5,300 km^2 per year between 2012 and 2015, very close to the 2020 target of 3,925 km^2. Disappointingly, however, deforestation has been increasing since 2016 (Inpe, 2017).

Several studies have analyzed the results, implications and future challenges of the decline in Amazon deforestation for climate change, PAs and biodiversity, public policy, economic and social benefits (Barreto et al., 2008; Nepstad et al., 2009; Rodrigues et al., 2009a; Assunção et al., 2013; Barretto et al., 2013; De Souza et al., 2013; Hargrave and Kis-Katos, 2013; Arima et al., 2014; Assunção and Rocha, 2014; Boucher et al., 2014; Nepstad et al., 2014; Soares-Filho et al., 2014; Assunção et al., 2015; Tollefson, 2015). Each of these studies contributes to compiling the pieces of this complex puzzle. Meanwhile, this study seeks to better explain which of these factors, whether singly or in combination, may have influenced the reduced rate of deforestation and land use change dynamics in the Brazilian Amazon, focusing on law enforcement.

1.2.1 Law enforcement

Environmental law enforcement is thought by some to have played a key role in reducing deforestation (Assunção et al., 2013; De Souza et al., 2013; Arima et al., 2014; Nepstad et al., 2014; Soares-Filho et al., 2014; Assunção et al., 2015). Meanwhile, some authors have suggested that any link may be only circumstantial (Schmitt and Scardua, 2015). The following paragraphs will present

[7] The PPCDAm is organized in three components: land tenure and land use planning, monitoring and control, and foster sustainable activities. The plan had over 180 activities involving partnerships between federal agencies, state governments, municipalities, civil society organizations and the private sector.

some previous studies surrounding the debate over the limitations, and some open questions regarding the influence of law enforcement on Amazon deforestation and land use changes.

Command and control strategies implemented by Ibama[8], combined with a very sophisticated forest monitoring system based on the development of satellite technology by Inpe (Kintisch, 2007; Brown and Zarin, 2013) have played a key role in reducing deforestation in the Brazilian Amazon (Taitson, 2011; Assunção et al., 2013; De Souza et al., 2013; Assunção and Rocha, 2014; Borner et al., 2014; Borner et al., 2015a; Schmitt and Scardua, 2015). For example, Ibama can intensify its presence in critical areas identified by INPE´s near real time deforestation monitoring system (DETER). In turn, once the system could identify deforestation in its early stages, this avoided extensive areas of deforestation. Furthermore, offenders knew that their actions were less likely go undetected (Taitson, 2011; Schmitt and Scardua, 2015). So far, increased patrol effort in priority areas has proved effective in diminishing illegal activity in the Amazon and is influencing land use change in critical areas (Barretto et al., 2013).

Despite all these advances, it remains important and necessary to better understand, and in more detail where, how and under what conditions law enforcement was most effective (Hargrave and Kis-Katos, 2013). All studies mentioned in the previous paragraphs used deforestation data up to 2012. However, the characteristics of deforestation have changed over time (2004-2015). For example, the number of deforested areas below 25 ha reached a peak of 63% in 2010, while the total area of deforestation it represented remained relatively stable (2005-2015). Two plausible explanations for these phenomena are outlined below.

First, determination of the law enforcement effort needed to reduce deforestation resulted in adopting the strategy of enforcing large polygons first, and leaving smaller polygons for later. Moreover, with daily information provided by the monitoring system, their presence was intensified in critical areas, so-called ‘hot spots’ of deforestation. Indeed, the strategy worked and numbers of deforested areas above 25 ha dropped significantly during this period. However, they had reached their limit and needed rethinking.

Second, the same daily monitoring system also provide information for the offenders, once the system became publicly available, as part of the transparency policy of the Brazilian Federal Government. Hence, offenders may have deliberately reduced the size of deforested areas to below 25ha, to infiltrate the surveillance system, even on large properties. However, some authors argue

[8] Ibama – Brazilian Institute of Environment and Renewable Natural Resources.

that is not the case. For them, small properties are responsible for the small polygons of deforestation, once 24% of deforestation in previous years (Inpe, 2015) comes from settlements, mostly comprising small properties. These behaviours remain unclear: do the monitoring systems and the law enforcement presence influence deforestation patterns (size)? Is this practice all over the Amazon, or it is possible to identify it only in specific areas or municipalities?

Even so, the recent availability of data on property limits may reveal a different effect of environmental law enforcement on deforestation in properties of different sizes. Brondizio and Moran (2012 p.81) presented ‘different variables to explain spatial patterns and temporal intensity of deforestation trajectories at different levels of analysis’. Consequently, their analysis suggested that possible patterns of deforestation may change again. In May 2016, Inpe released the new daily monitoring system, using Resourcesat2 data (Indian satellite), that is capable of detecting deforested areas as small as 3ha (Diniz et al., 2015).

In addition, an unexpected pattern of behaviour showed itself in rates of deforestation during the last four years, in which large areas (>500ha) are gradually coming back (MMA, 2018). This might relate to the sense of impunity that was argued by Taitson (2011) and Schmitt and Scardua (2015), given that only 2% of the fines are paid. Thus, the offenders have given signs that they will continue to challenge the capacity of the environmental law enforcement agencies, possibly with the idea that it is still worth taking the risk.

It is important, therefore, to extend the analysis into two dimensions, over both temporal and spatial scales, in order to provide information for new strategies and more tailored policies to improve governance. A good path is to break the 5,300 km^2 ‘barrier’, reach the 2020 target, and mitigate emissions from deforestation (Brazil, 2009). Another good path is to go beyond the *‘Zero Deforestation by 2030’*, as expressed in the “New York Declaration on Forests”, at the United Nations Climate Summit in 2014; as desired by Brazilian and global society (UN, 2014); and the pledges of the Consumers Goods Forum to achieve zero net deforestation by 2020.

Law enforcement has also had effects on other factors, like land use changes, and influencing the economy of important commodities such as soy and beef. One clear example is the Brazilian soy moratorium that imposes restrictions on soy cultivation in areas deforested after 2008[9]. This agreement between government, civil society and productive sector, producers, traders and buyers of soy, lasted for over 10 years and had the aim of producing ‘responsible soy’ that does not

[9] It started with 2006 as the threshold year, but moved to 2008, as a new agreement to be in accordance with the new passed Forest Law in 2012 (see Section 1.4 for more details).

contribute to Amazon deforestation. The traders of Brazilian soy always consult Ibama's fines and embargoes web system to check whether or not the property is listed by the environment agency. If so, they will not buy their soy, to avoid sharing responsibility for an illegal activity. For instance, the last report of the soy moratorium shows that only 1% of Amazon soy is not in compliance with the Soy Moratorium (Abiove, 2017). So, law enforcement is influencing the market and its dynamics, and is discouraging the occurrence of new environment violations.

Given the discussion above, the first step for this study was to undertake an analysis of the relationships between command and control, and deforestation. In other words, to answer the question: how and to what extent does environmental law enforcement influenced rates of deforestation in the Brazilian Amazon? There is some evidence of a negative correlation between law enforcement and deforestation in the Amazon region (Taitson, 2011; Assunção et al., 2013; Assunção and Rocha, 2014; Assunção et al., 2015; De Souza and De Marco, 2015; Schmitt and Scardua, 2015). However, other authors argue that government agriculture credits and loans stimulate deforestation all over the Amazon region (Alencar et al., 2004). My proposal here was to investigate the direction and extent of the inspections effects at the municipality level. It was predicted that examining this question at this scale might reveal new nuances of surveillance performance and its local impacts on environmental, social, and economic factors.

1.3 Land use change

On climate change, Section 1.1 argued that land use change (AFOLU) is a very complex chain of interconnected sectors, including agriculture, livestock, bioenergy and forest conservation, that present huge challenges in dealing with the intensified competition for land (Cabeza et al., 2010). This study aimed to investigate specific transitions in land use in the Amazon: forest, agriculture, livestock and natural regeneration[10]. For the purpose of this study, deforested areas are the starting point for all the land use transformations.

The global scenario for agricultural expansion points to a key role for developing countries (Phalan et al., 2013). In many countries this represents the loss and conversion of natural areas for export oriented commodities. For Hall (2015 p.408) it is the 'global land grab': large-scale land acquisition across the South by foreign and domestic investors, for food and bioenergy production, to supply the

[10] For the purpose of this study, natural regeneration is an area that undergone a clear cut sometime in the past and abandoned for some reason. Now it is naturally returning to its original condition through a secondary vegetation succession process.

increasing global demand for a growing world population. Some authors argue that globalization and neoliberal policies are shaping development and conservation in rural areas (Hecht and Saatchi, 2007; Hecht, 2010). At the same time, recent analyses show that most of the expansion into agriculture is attributed more to intensification than to expansion (Angelsen and DeFries, 2010; Phalan et al., 2014; FAO, 2015; Meyfroidt et al., 2018; Thomson et al., 2019) and a similar pattern holds in Brazil (Nepstad et al., 2014). However, this relationship may be circumstantial, because any increase in global demand may again result in area expansion (Balmford et al., 2012; De Souza and De Marco, 2015). Worse, Phalan et al. (2013) argue that this expansion in developing countries may occur on priority areas for conservation.

Historically, land use change in the Amazon has mostly been driven by the expansion of a vast agricultural frontier including: livestock and agriculture; illegal logging; illegal gold mining; and infrastructure projects such as dams and paved roads. After deforestation, livestock is the main land use (Moran, 1981; Fearnside, 1983; Hecht, 1985; Hecht, 1989; Hecht, 1993a; Moran, 1993; Walker et al., 2000; Lambin et al., 2001; Margulis, 2003.; Fearnside, 2005; McAlpine et al., 2009). This relationship is not exclusively related to the increased capacity of the Brazilian production to meet the growing demands, both in domestic and international markets. Instead, the consolidation of pasture is also strongly related to public land grabbing, because pastures are planted to add value and a sense of ownership to illegally appropriated land, which is trading using false documents (Simmons et al., 2007; Reydon et al., 2015). As a result, livestock are widespread in the Amazon regardless of property size (Fearnside, 2005; McAlpine et al., 2009; De Souza et al., 2013; Fearnside et al., 2013).

As part of PPCDAm action plan, the TerraClass[11] programme was launched in 2008 to answer a simple, but very important question: 'What use is made of deforested areas in the Amazon?' This question is key to understanding the land use transitions currently occurring in the Amazon. The 2014 result shows that deforested areas represented over 18% of the Amazon biogeographical region. These areas were classified into 14 types of coverage and land use: annual agriculture; four different types of pasture use intensity; land use mosaics; secondary vegetation (natural regeneration); reforestation; mining; urban areas; water; areas not observed; clouds and others (Appendix 9.2 – Table *S* 2.2). To highlight the most representative classes, the figures showed that 63% of areas were pastures, 6% were of annual agriculture and 23% of secondary vegetation resulting from natural regeneration (Inpe, 2016b).

[11] Terraclass – Land use survey in the Amazon. The study aims to qualify deforested areas in the Amazon, using as a basis the mapped deforested areas published by PRODES.

The drastic reduction of deforestation and the more systematic presence of surveillance poses a new situation: the restriction on the availability of forests for conversion and expansion of agriculture/livestock, once the transaction risk increased. Thus, surveillance may influence the reshaping of land use in the Amazon, bringing up the second main question for this study (Question 2): How and to what extent is land use change being influenced by environmental law enforcement? If so, what paths do producers and landowners chose to increase their yields? They may make better use of cleared areas, like implementing a second crop per year or a rotation between agriculture and pasture. If this is an observable phenomenon, is it widespread or can it be found in specific regions, and which regional attributes can explain it? To search for answers to all these questions, I broke down the main question into two. First, what is the extent and direction of law enforcement influence on land use change, named, livestock, agriculture and natural regeneration, across the Amazonian municipalities? Second, to what extent and direction these possible changes will influence small, and medium-large properties?

Consequently, this part of the study aims to contribute to filling the gap with more detailed analysis of land use dynamics resulting from systematic law enforcement since 2004.

Meanwhile, in the climate change mitigation equation, forest restoration is key as carbon sinks and for biodiversity conservation. According to SCBD (2003), it is estimated that 60-87 GtC represents the potential mitigation delivered by afforestation, reforestation, avoided deforestation and degradation, until 2050. However, until very recently, ‘forest restoration has generally been “below the radar” in the tropics’ (Hecht and Saatchi, 2007 p.670), and requires further investigations. Hecht (2010) reported many cases of forest restoration under very different circumstances, trying to persuade and revert the catastrophic emphasis on deforestation in the tropics.

Market globalization and the technological advances in agriculture also probably contribute to forest restoration. The large-scale (high concentration of lands) and highly mechanized activities in rural areas are putting the small farmers at a disadvantage to compete in a global economy. The result is the abandonment of their land and migrating to urban areas, a phenomenon identified in different regions around the planet, but especially in the tropics (Lambin et al., 2001; Brockhaus et al., 2012; Smith et al., 2014).

In the Brazilian Amazon, the ongoing increase in surveillance, fines and embargoed areas in the last decade, has probably played a key role in the increase of abandoned areas that were formerly mostly involved in illegal activities, and the consequent migration of farmers and rural workers to urban areas.

As a result, the 2014 land use mapping detected that 23% (173,387 km^2) of all deforested areas were restoring naturally. These figures indicate the likelihood that a carbon sink will develop. Taking this together with the consistent decline in deforestation rates may result in a change of status for the Amazon, from carbon source to carbon sink.

So, given the main focus of this study is to investigate the effects of law enforcement at the municipality and property levels, the specific Question (3) that will guide the investigation on natural regeneration is 'To what extent and direction will embargoed areas and surveillance operations influence the persistence of natural regeneration over the study period?'

Finally, the Brazilian experience in combating deforestation is not restricted to environmental concerns. It also incorporates the social and economic dimensions of the problem and 'provides valuable lessons about the importance of public policies, monitoring systems and interventions in the supply chain to reduce the advance of the agricultural frontier' (Nepstad et al., 2014 p.1123). It is an action for sustainable development, with all the challenges, obstacles and opportunities the concept embraces. This has been the basis for the new concept for the development of the Amazon, called Protection and Production[12].

In essence, my approach to this problem has been that land is a national asset and therefore should be most efficiently utilised. To do that, *inter alia*, public, private and academic sectors, and civil society require a better national understanding of key issues. This territorial approach to deforestation has been effective and could consolidate the results achieved in reducing deforestation by providing a favourable environment for other dimensions of sustainable development (Nepstad et al., 2014). In other words, a strong and modern agricultural sector can grow at the same time as the landscape of which it is a part, and can help maintain natural areas (Boucher et al., 2014). A similar concept was coined by Defries and Rosenzweig (2010), who called it a whole landscape approach that combines the increased productivity of agriculture with conservation and restoration of natural environments. Reed et al. (2015) proposes something similar: 'A landscape approach can be defined as a framework to integrate policy and practice for multiple competing land uses through the implementation of adaptive and integrated management systems'.

The combination of land use dynamics, analysis, rural environmental registration (CAR) and economic and social development indicators from government will allow a more detailed level of analysis of the dynamics of environmental law enforcement, deforestation and land use in the Amazon region.

[12] Aims to encourage changes in current patterns of management and investment in order to build a solid foundation for future low carbon economic development and environmental conservation.

This goes well beyond what has been possible so far. Indeed, the results may indicate and provide valuable information to answer the central question of this study, as well as make it possible to identify the municipalities and/or properties with similar characteristics in land use dynamics. If these groups emerge as important from the analysis, this may provide insights and subsidies for the design of more specific and 'tailored policies' to operate at different levels (Brondizio and Moran, 2012). Therefore, these authors note that '…Amazon-wide analyses obscure important inter- and intra-regional processes and interactions, such as the differential impact of development policies and commodity markets, and to identify where successful efforts to stop or reverse deforestation have taken place.' (Brondizio and Moran, 2012 p.70)

In summary, the outputs of this study intend to contribute to the mitigation and adaptation of GHG emissions from land use and forests in Brazil. In doing so, I aim to make an important contribution to Brazilian NDC[13]. This was agreed in Paris to reduce emissions by 37% in 2025 and 43% by 2030, against a 2005 baseline (Brazil, 2015).These targets were received by the international community as one of the most ambitious NDCs.

1.4 Forest Code and CAR

Brazil passed new environmental legislation in 2012 (Federal Act 12,651 25 May 2012). The Act was consolidated after a long and historic debate in Congress that mobilized all stakeholders: environmental NGOs, civil society, agribusiness, government, and the judiciary. The Brazilian Congress was at the centre of a hot debate around the new and extremely polarized Forest Code. In one corner, the environmentalists argued to keep the environmental legislation strong, restrictive, and lobbied for more restrictions. In the other corner, the "*ruralistas*", the agricultural lobby/group in Congress, argue and pushed for less restrictions, and the relaxation of the Forest Code, to make it more permissive, in order to facilitate the advancement of agribusiness. The main arguments of agribusiness revolve around the importance of agriculture in the country's trade balance, accounting for a significant portion of exports, the need to expand to meet the growing global demand for Brazilian agricultural commodities and food security. In a nutshell, very restrictive legislation could jeopardize the country's development and restrict the generation of jobs related to the agribusiness industry.

[13] NDC – National Determined Contributions, UNFCCC language.

The counter argument of environmentalists, based on their technical and scientific arguments, showed throughout the debate in the Congress that there is no need to further expand the areas under agriculture. Instead, the aim should be to use what is already deforested more efficiently. For instance, livestock farming in Amazonia has a low pasture occupation, a little more than one head per ha. An increase in occupancy to 1.5 per ha could free space for agriculture, and supply the growing global demand for two global commodities, soybeans and meat. Using fairly simple measurements such as pasture rotation, pilot projects have already shown that productivity can increase, thereby sparing land for agriculture to expand. However, the current varieties of soybean cannot currently increase their productivity. But, it is also argued this may have an opposing effect. The profit-driven producer, noting that his productivity has increased, may wish to expand activities. For example, he could increase his cattle herd to occupy his entire available area. Consequently, he would not spare land areas for agriculture or conservation. Ultimately, neither side was completely satisfied with the approved version of the new legislation. Despite the polarized debate and criticisms from both sides, the final text reached a reasonable balance between conservation and rural development. In the end, the approved text brought some advances that will certainly have a positive influence on both agendas.

A consensus outcome of the new environmental legislation was the rural environmental registry system known as CAR (Cadastro ambiental rural, free translation in Portuguese). CAR became compulsory throughout the Brazilian territory. Taking an extremely simplistic view of this development, on the one hand, environmentalists will have a tool to better control compliance of environmental legislation at the property level. On the other hand, many in the agribusiness sector evaluate CAR as a benchmark for environmental compliance of Brazilian farmers and ranchers. CAR became important for the export of agricultural commodities, as the international market increasingly demanded a clean supply chain. Hence they wished to avoid contributing to the destruction and degradation of natural environments, especially tropical forests. Thus, those owners who are compliant with the legislation will have unrestricted registrations, a “green flag”. Last but not least, information can be directly verified on the internet by buyers, as the system is open to queries about properties compliance.

CAR is a comprehensive electronic registry, georeferenced with detailed mapping of private property limits, legal reserves, permanent preservation areas and land use, based on 5m spatial resolution images (Rapid Eye[14]), mandatory for all rural properties. A strategic database for the control,

[14] https://directory.eoportal.org/web/eoportal/satellite-missions/r/rapideye

monitoring and combat of deforestation in Brazil, as well as for environmental and economic planning in rural properties.

The CAR system is being implemented in phases: registry (almost concluded); compliance verification; environmental recovery programme (PRA) agreements signed for properties in debt with the environmental regulations; and monitoring the implementation of PRA. A transition phase for property compliance involving fine suspension, as long as landowners implement their recovery plan.

By 2018, 5.5 million rural properties had already been registered, and a total area of 470 million ha inserted in the database of the integrated system. The registry is implemented by the states, and coordinated by the Ministry of the Environment until the end of 2018[15], providing the necessary tools and integrating the information into a single national registry system. Certainly, the registry will take us to another level of understanding of land use in Brazil, for the benefit of more tailored public policies in pursue of sustainable development.

A priori, based on practice and preliminary results, I expect the policy to influence the curbing of deforestation. This curb will mostly be influenced by the environmental law enforcement field operations having a positive influence on reducing deforestation, and increasing natural regeneration through passive means. On land use, mainly annual agriculture and livestock, it will be possible to find positive and negative effects, depending on how landowners react to dealing with the implementation of the policy against deforestation. In terms of socio-economic indicators, the municipalities may show better or worse performances, depending on how much its activities are based on halting illegality, but reducing law enforcement operations and other governmental policies initiatives.

1.5 Objectives

This extensive literature review suggests that the main objective of this research should be to increase knowledge on the influence of environmental law enforcement, mostly comprising ground operations in the Brazilian Amazon region, on deforestation, land use change and the persistence of natural regeneration by exploring the following more specific questions:

1. How and to what extent has environmental law enforcement influenced rates of deforestation in the Brazilian Amazon at the municipality level?

[15] currently under the responsibility of the Ministry of Agriculture.

2. What is the extent and direction of environmental surveillance influence in reshaping land use change of livestock, agriculture, and natural regeneration, across the Amazon municipalities and different property sizes after the approval of the priority municipalities' policy in 2008?

3. To what extent and direction has law enforcement influenced the persistence of natural regeneration over the study period?

1.6 Outline of chapters

In Chapter 2, I will introduce the Amazon region by characterizing deforestation and land use change at different scales of land tenure, presenting different perspectives and a solid background for the importance of the Brazilian Amazon region for this study. In Chapter 3, I will provide a summary of the most important data needs for this study, followed by a more detailed presentation of the two techniques adopted to investigate the possible influence of law enforcement. I will close by presenting the Policy for the Priority Municipalities. In Chapter 4, I will assess the influence of law enforcement on forest loss reduction with a spatial analysis at the municipality level. In Chapter 5, I will explore a possible co-benefit of law enforcement on land use change, focusing on annual crops, livestock and natural regeneration at the municipality level and for private properties, both small and large, as well as for settlements. I will apply a very new technique that combines difference-in-differences with entropy balancing. In Chapter 6, I present results of the possible influence of law enforcement on the persistence of over 41,000 km2 of natural regeneration over the 10 years of the study. Last but not least in Chapter 7, I will draw some final remarks and the conclusions of this work.

2 Study area

Amazonia is superlative in many respects.

First, the Amazon is the world's largest contiguous rainforest. It covers over 6 million km2, half of which remains in tropical forests that border the nine countries of the Amazon, comprising: Brazil, Bolivia, Peru, Ecuador, Colombia, Venezuela, Guyana, Suriname and French Guiana. These countries cover nearly 40% of South America's territory. Nearly two-thirds of the Amazon rainforest is found in Brazil.

Second, the Amazon rainforest is home to the largest river by volume on the planet. The Amazon River holds around 20% of global fresh waters.

Third, the Amazon supports an incredible biological and cultural diversity. This includes one in ten known species on Earth, the highest diversity of plants, one in five of all described bird species, and millions of insect species, among which most still remain undescribed.

Fourth, the Amazon is also home to over 30 million people, including indigenous and ethnic groups, some of whom still remain to be discovered. Fifth, Amazonia is estimated to store 10% of the world's carbon, and is the largest store of tropical timber on the planet.

Sixth, 70% of South America's GDP is produced in areas that receive rainfall or water from the Amazon'[16].

The Amazon Biome in Brazil (Figure 2.1) covers almost 50% of Brazil's national territory, 4,196,943 km2 (IBGE, 2004). Over 42% of this biome is set aside as PAs or indigenous lands, and 18% is already deforested (Inpe, 2017) (Figure 2.2), as well as one of the main sources of land use CO_2 emissions globally (IPCC, 2014a; Smith et al., 2014).

This study adopts the political and economic border of the Amazon, the so called, Brazilian Legal Amazon (BLA) which was established as a political area to promote and improve the social economic development of the region (Brazil, 1953; Brazil, 1966). It accounts for 5,217,423 km2, corresponding to 61% of Brazil's territory (Figure 2.1), in 772 municipalities[17]. Currently, it corresponds to the area

[16] Mongabay - https://rainforests.mongabay.com/amazon/amazon-rainforest-facts.html . Accessed on 06Sep2017.

[17] I have excluded from the analyses the municipality of Mojui dos Campos, in Pará state, officially emancipated only in 2013, almost at the end of the study timeframe considered, and for obvious reasons do not have data available for all the period. So, 771 municipalities are considered in the BLA.

of the states of the north region (Acre, Amapá, Amazonas, Pará, Rondônia, Roraima and Tocantins), plus the totality of the state of Mato Grosso and the municipalities of the state of Maranhão located west of the meridian 44° W. The BLA is the least populated region of Brazil with 25 million inhabitants, of whom over 75% are concentrated in urban areas.

In the Amazon, land tenure is a complex and a persistent topic, resulting in land disputes, overlaps, and land grabbing, among other problems (Azevedo-Ramos and Moutinho, 2018). Table 2.1 presents the area covered by different categories of land tenure: PAs, indigenous lands, rural settlements, undesignated federal public lands, and private properties (CAR)[18]. Regarding PAs categories, it is important to distinguish the very unrestricted Environmental Protected Areas (APAs) from other categories when summarizing information or overlapping with deforestation and land use change, as in Table 2.1. APA are very extensive areas, usually consolidated with human occupation, including public and private lands. Their implementation does not displace the resident population and allows economic activities.

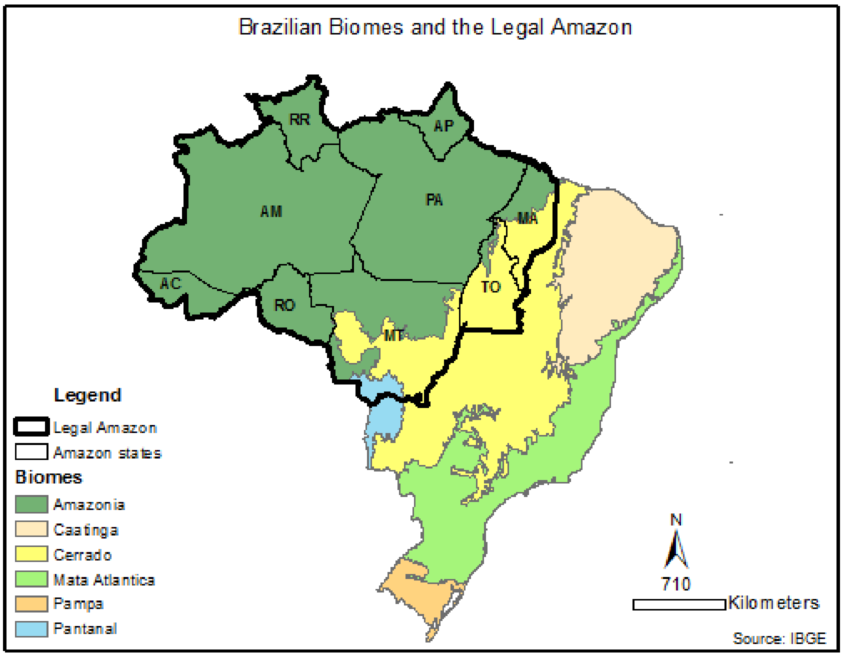

Figure 2.1 – Brazilian Biomes: Amazonia, Cerrado, Caatinga, Pantanal, Atlantic Forest and Pampa. The Brazilian Legal Amazon states (9): Acre (AC), Amazonas (AM), Amapá(AP), Maranhão(MA), Mato Grosso(MT), Pará(PA), Rondônia(RO), Roraima(RR), and Tocantins(TO).(Source:IBGE)

[18] There are some overlaps between different categories, like protected areas and indigenous lands and so on. In Table 2.1, the overlaps were not eliminated. So, the total sum displayed may exceed the total area of a state territory and the Legal Amazon. Meanwhile, some information gaps exist in other areas.

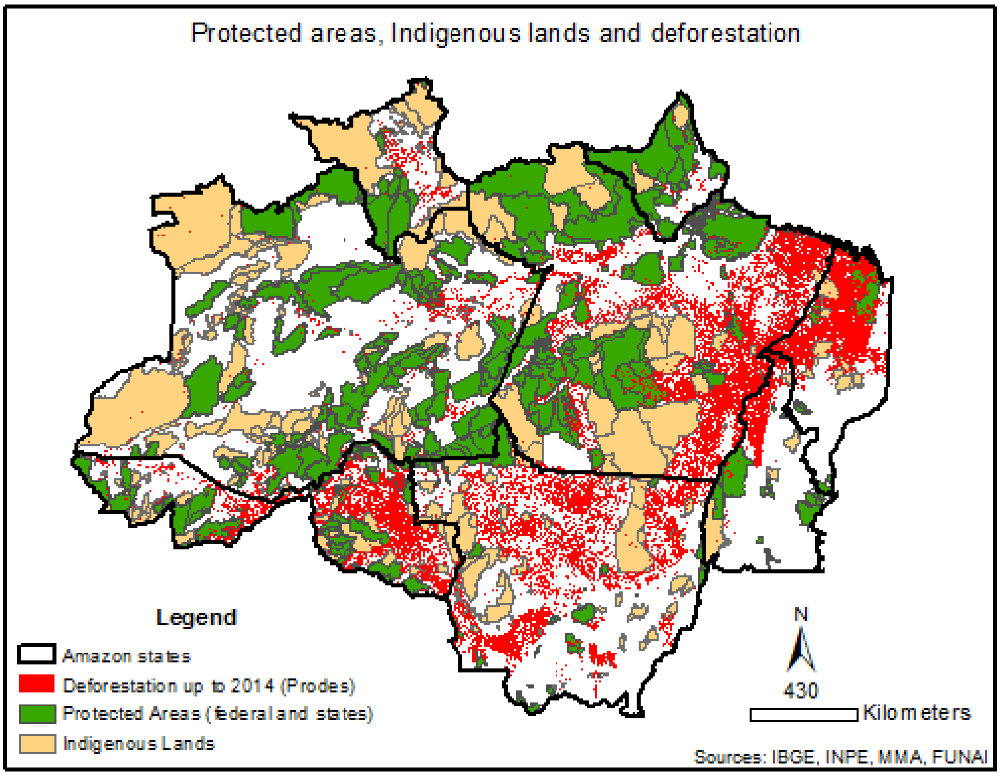

Figure 2.2 – Amazon protected areas, indigenous lands and deforestation (Sources: IBGE, INPE, MMA, FUNAI)

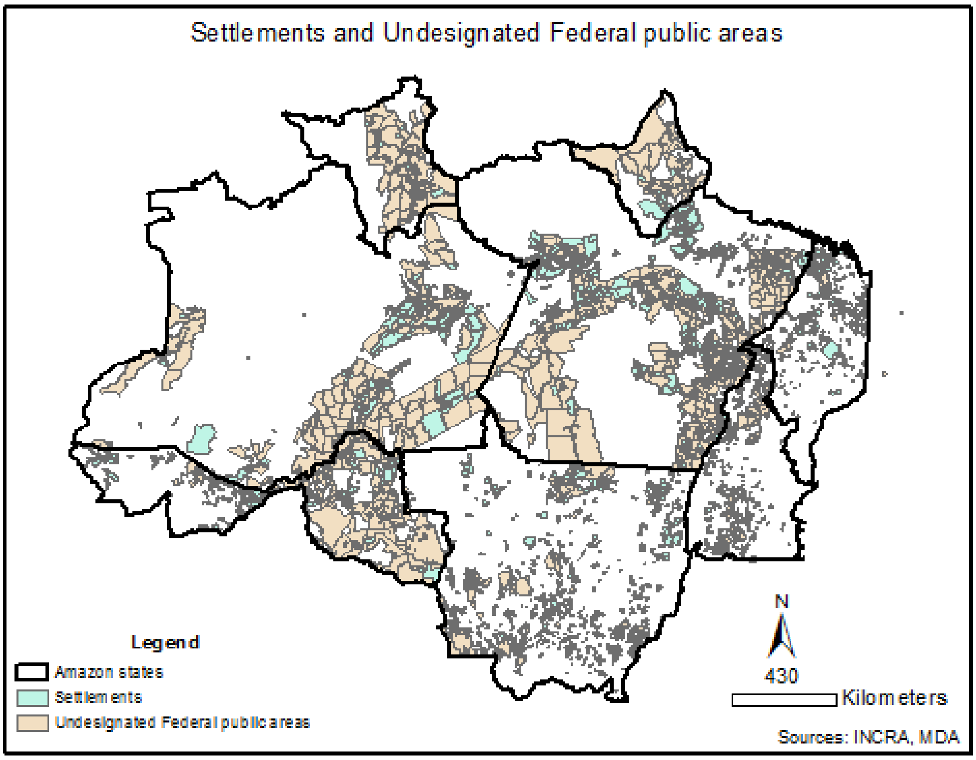

Figure 2.3 – Settlements and Undesignated Federal public areas within the Brazilian Legal Amazon (Sources: INCRA,MDA)

Table 2.1 – Land tenure of the Brazilian Legal Amazon, by states: strict preservation and sustainable use protected areas (federal, state, municipal), Indigenous lands, Rural/Land reform Settlements, Undesignated Federal public lands, private properties – the environmental rural registry (CAR – acronym in Portuguese.) (Sources: MMA, FUNAI, INCRA)

Categories (km2)/states **Protected Areas**	Acre	Amapá	Amazonas	Maranhão	Mato Grosso	Pará	Rondônia	Roraima	Tocantins	Total*
Federal (total)	40,457	57,770	263,958	9,097	18,766	205,346	33,979	16,071	13,821	659,264
Strict Preservation	9,141	47,843	132,409	7,919	16,074	78,070	24,192	11,660	13,172	340,481
Sustainable use (except APA)	31,316	9,928	130,024	1,157	1	101,807	9,787	4,410	134	288,565
Environmental Protection Area (APA)			1,524	21	2,690	25,470			515	30,219
State (total)	7,548	32,699	188,434	28,286	24,111	201,925	20,667	15,750	23,534	542,955
Strict Preservation	6,939	40	34,996	33	14,589	54,748	8,958	124	2,989	123,416
Sustainable use (except APA)	257	32,434	136,456		1,468	78,580	11,642			260,836
Environmental Protection Area (APA)	352	226	16,982	28,253	8,054	68,596	68	15,626	20,545	158,702
Municipal (total)		4	1,030		755	8		16,020	15	17,832
Strict Preservation		4			1	8			15	28
Sustainable use (except APA)			122			0				122
Environmental Protection Area (APA)			908		754			16,020		17,683
Indigenous lands/territories	25,320	11,834	455,646	24,393	149,638	307,539	51,079	103,802	25,907	1,155,158
Settlements	17,997	11,832	81,389	28,146	40,516	136,308	23,938	11,706	11,660	363,492
Undesignated federal public lands	6,653	80,373	356,898	10,628	85,505	417,359	160,116	107,502	27,500	1,252,535
Private properties: **Rural Environmental Registry (CAR)**	94,668	33,895	312,261	202,271	733,836	609,297	125,323	48,374	172,471	2,332,395
TOTAL	192,643	228,408	1,659,616	302,821	1,053,127	1,877,782	415,103	319,225	274,908	6,323,631

*The total value of the Table exceeds the legal Amazon area because the overlaps have not been eliminated.

The following two sections (2.1 and 2.2) aim to present perspectives of Amazon deforestation and land use change. This characterization does not intend to be exhaustive. Rather the chapter calls the reader’s attention and provides basic information for some important aspects of deforestation and land use dynamics related to the main questions of this study, which will be further analyzed in Chapters 4, 5 and 6.

2.1 Characterization of the Brazilian Amazon deforestation at different scales

Broad patterns of deforestation

Brazil has conducted satellite monitoring of the Amazon since 1988, to produce data on annual rates[19] of deforestation that are used by the Brazilian government for implementing public policies in the region (Figure 2.4). The characterization of deforestation that follows will concentrate on 2002 and onwards, when Inpe updated and adopted their current methodology.

The history of deforestation monitoring in the Amazon can be divided into two distinct periods: before and after the implementation of PPCDAm in 2004. The first period, before PPCDAm, is characterized by two reductions soon followed by years of constant increases in deforestation (Figure 2.4).

By contrast, the PPCDAm period showed a consistent rate of reduction of 76% over 13 years (2004-2017), alongside the four phases of implementing the Action Plan. The first phase revealed a sharp drop in forest loss of 53%, with an average of 17,127 km2/year. In the second phase, the reduction continued but at a slower pace, with an average rate of deforestation of 6,961 km2/year. This represented, another impressive reduction of 59% compared with the first phase. The third phase registered the lowest rates of deforestation, with an average of 5,420 km2/year, but showing annual fluctuations. In 2016, the fourth phase began with an increase in deforestation to 7,893 km2/year, returning to the level of the initial year of the second phase (2009), raising a yellow flag. This was followed by the resumption of deforestation in 2017, at a rate that was still higher than rates seen in the third phase (Figure 2.4).

Despite this impressive reduction of 70% in rates of deforestation in relation to the average of 19,625 km2/year for the period 1996-2005[20], Brazil still remains 2,700 km2 distant from its 2020 National Climate Change Policy target, to reduce deforestation by 80%, to 3,925 km2 (Brazil, 2009).

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[19] PRODES – Deforestation monitoring program is led by the National Institute for Space Research (INPE) to produce the annual deforestation rates for the Amazon region using 20-30m resolution satellite images from different sources: LANDSAT, CBERS, LISS-3(Resourcesat-1), UK-DMC2 and more recently the Sentinel constellation. Initially, the period 1988-2002, the monitoring was done by visual interpretation on printed satellite images, mostly Landsat, followed by digitalization of the polygons. Only in 2002, it has evolved for digital classification, checked and edited by experienced interpreters.

[20] Period used to calculate the Brazilian government voluntary commitment, assumed in 2009, to reduce deforestation in 80% by 2020.

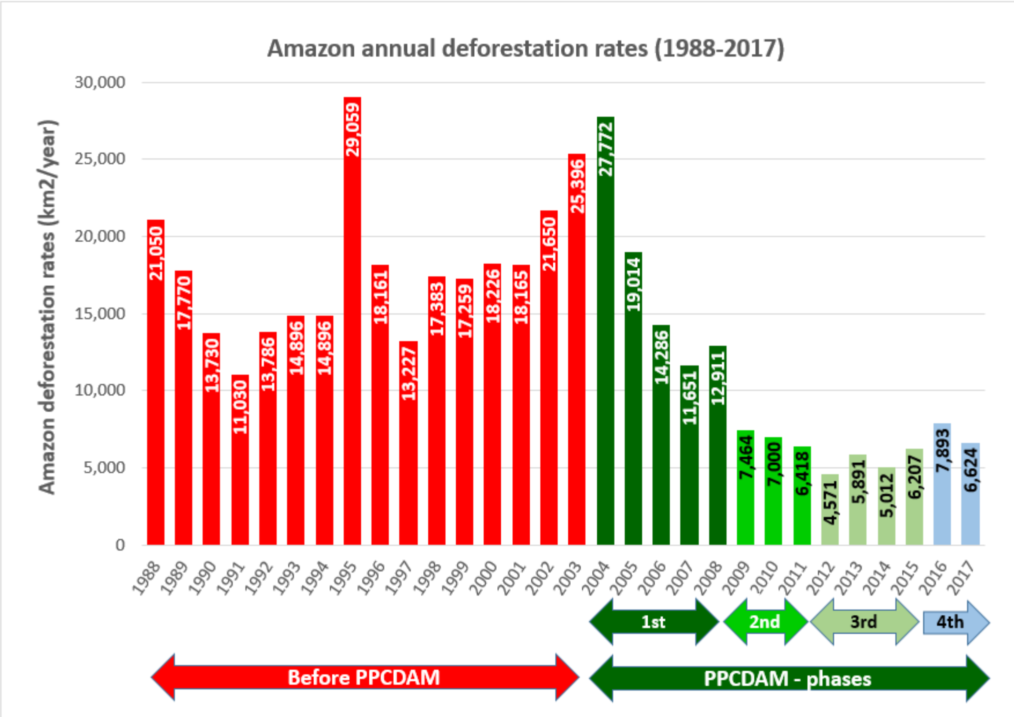


Figure 2.4 – Annual rates of deforestation in the Brazilian Legal Amazon for the period 1988-2017. The chart highlights the four phases of the Action plan to prevent and control deforestation (PPCDAM). (Source: PRODES/Inpe)

Deforestation by States

Historically, deforestation has been concentrated within three states: Pará (PA), Mato Grosso (MT) and Rondônia (RO). However, the share of forest loss in these three states has steadily decreased from 88% in 2004 to 76% in 2017. By contrast, groups in the second level, including Acre (AC), Amazonas (AM) and Maranhão (MA), showed an upward trend in their rates of deforestation, from 10% in 2004 to 22% in 2017. This increase was mostly driven by increased rates of deforestation in the south of Amazonas state. These data suggest that the frontier of deforestation is moving towards the centre of the Amazon region, further expanding the arc of deforestation. Rates of deforestation in the third group of states: Amapá (AP), Roraima (RR) and Tocantins (TO) varied between 2% and 6% (Figure 2.5 and Table 2.2).

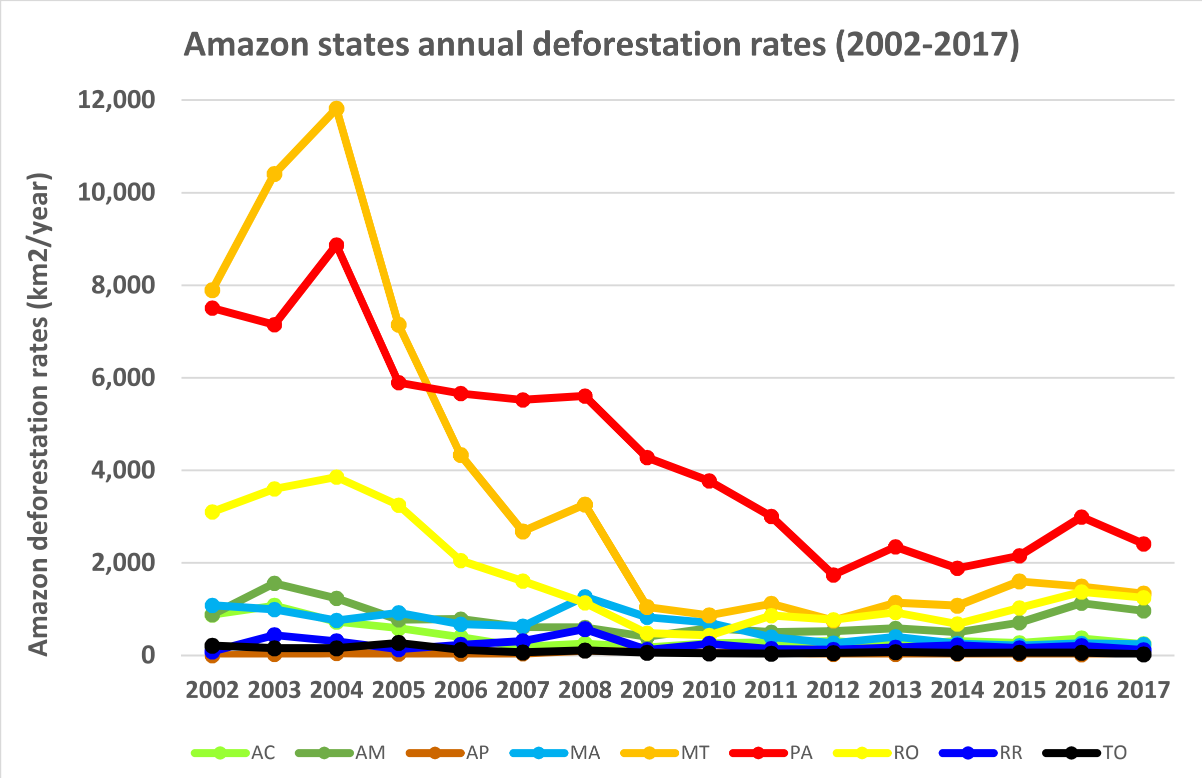


Figure 2.5 – Annual Deforestation rates (km2) for the period 2002-2017, in the nine states of the Brazilian Legal Amazon: Acre (AC), Amazonas (AM), Amapá (AP), Maranhão (MA), Mato Grosso (MT), Pará (PA), Rondônia (RO), Roraima (RR) and Tocantins(TO).(Source:Prodes/INPE)

Table 2.2 - Deforestation rates (km2) for the period 2002-2017, in the nine states of the Brazilian Legal Amazon: Acre (AC), Amazonas (AM), Amapá (AP), Maranhão (MA), Mato Grosso (MT), Pará(PA), Rondônia (RO), Roraima (RR) and Tocantins(TO). (Source:Prodes/INPE)

Year	AC	AM	AP	MA	MT	PA	RO	RR	TO	Amazon
2002	883	885	0	1,085	7,892	7,510	3,099	84	212	21,650
2003	1,078	1,558	25	993	10,405	7,145	3,597	439	156	25,396
2004	728	1,232	46	755	11,814	8,870	3,858	311	158	27,772
2005	592	775	33	922	7,145	5,899	3,244	133	271	19,014
2006	398	788	30	674	4,333	5,659	2,049	231	124	14,286
2007	184	610	39	631	2,678	5,526	1,611	309	63	11,651
2008	254	604	100	1,271	3,258	5,607	1,136	574	107	12,911
2009	167	405	70	828	1,049	4,281	482	121	61	7,464
2010	259	595	53	712	871	3,770	435	256	49	7,000
2011	280	502	66	396	1,120	3,008	865	141	40	6,418
2012	305	523	27	269	757	1,741	773	124	52	4,571
2013	221	583	23	403	1,139	2,346	932	170	74	5,891
2014	309	500	31	257	1,075	1,887	684	219	50	5,012
2015	264	712	25	209	1,601	2,153	1,030	156	57	6,207
2016	372	1,129	17	258	1,489	2,992	1,376	202	58	7,893
2017	244	965	31	237	1,341	2,413	1,252	115	26	6,624

The Brazilian policy to curb deforestation was launched in 2004. That year, Mato Grosso (MT) was the ‘champion’ of deforestation with 11,814 km2/year, followed by Pará (PA) with 8,870 km2/year. In the first phase of PPCDAm, both states substantially reduced their deforestation rates and switched positions (Figure 2.5). After 2006, Pará became the state with the highest rates of forest loss, with a peak of 57% share in 2009 (Table 2.2).

In the third phase, rates of deforestation almost doubled in Amazonas state, and its contribution to deforestation rose from 6% (annual average of the 1st and 2nd phases) to 11% (annual average of the 3rd and 4th phases). Acre also increased its participation in the third phase to 5% compared to 3%, the annual average of the 1st and 2nd phase. On the other hand, Maranhão has reduced its involvement from a peak of 11% in 2009 to only 3% in 2016.

In the first group, Pará remains with the largest share of deforestation, and an annual average of 38%, followed by Mato Grosso, which fluctuated between 17 and 26%, and Rondônia with an annual average of 16%.

Finally, the fourth phase (2016-2017) indicated a new configuration, with Pará isolated as the largest contributor to deforestation, followed by the second level group of states: Mato Grosso, Rondônia and Amazonas. Meanwhile, the third level included the remaining five states: Acre, Maranhão, Amapá, Roraima and Tocantins (Figure 2.5).

Deforestation by Municipalities

Moving to the municipality level, 50% of annual deforestation was restricted to less than 5% of the 772 Amazon municipalities, and 16% of the Legal Amazon area. Moreover, deforestation became more concentrated throughout the PPCDAm implementation, decreasing from 39 to 28 municipalities for the period before PPCDAM to its 3rd phase (13 years). In terms of area, the concentration has a similar but less intensive pattern from 17.4 to 16.3% of the Legal Amazon. (Table 2.3).

Table 2.3 – Concentration of 50 and 75% of annual deforestation in the 772 municipalities of the Legal Amazon in four periods: prior to, and, in the three phases of PPCDAM, in number of municipalities and percentage of the total area of the Legal Amazon. (Source:Prodes/INPE)

Annual Deforestation	Municipalities	2002-2004 (prior PPCDAM)	2005-2008 (1^{st} phase)	2009-2011 (2nd phase)	2012-2015 (3rd phase)
50%	Number	39	34	32	28
	Percentage of the Legal Amazon area	17.4%	15.9%	15.7%	16.3%
75%	Number	100	91	93	82
	Percentage of the Legal Amazon area	28%	29%	33%	31%

In 2002, the 50% annual forest loss was intensive in Mato Grosso and Pará, including 22 and 14 out of 41municipalities, respectively. In 2015, forest loss moved into the Amazon, to the southern region of Amazonas state that itself became a deforestation hotspot with 4 municipalities, together with new areas in Pará, which became the leading deforestation state with 12 out of 25 municipalities deforested. Nevertheless, only 11 municipalities remain as top priority in both years, 2002 and 2015. Of these, six are in Pará, three in Rondônia and 1 in Mato Grosso and Amazonas (Figure 2.6).

The second line of Table 2.3 shows the 75% concentration of deforestation, with the same trend as 50%, for the number of municipalities, from 100 to 82 for the period before PPCDAM and its 3^{rd} phase, respectively. However, the percentage of the Amazon area showed an increasing trend of deforestation from 28 to 31%.

Listed and non-listed municipalities

The second phase of PPCDAm started just after it was passed to the priority list policy (see Chapter 3 for details), and the figures suggest that this policy had an immediate effect. Priority municipalities produced a more pronounced cuts in deforestation rates, 63%, compared to 54% for unlisted municipalities. In absolute terms, the first phase clearly shows more deforestation in listed municipalities, and this was reversed during the second phase which retained the same level during the third phase (Table 2.4).

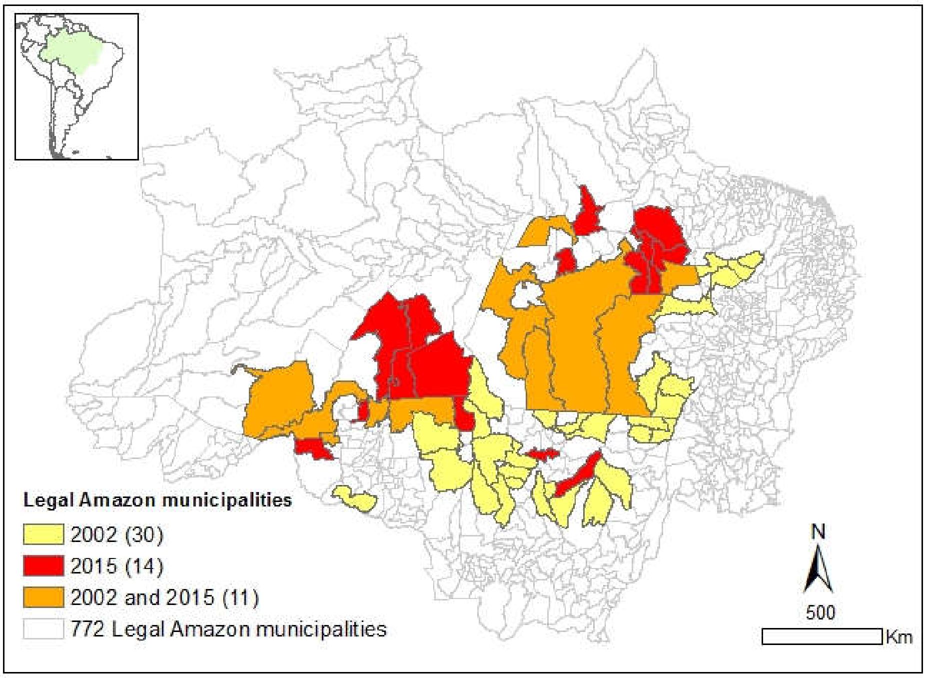


Figure 2.6 – Municipalities that concentrates 50% of deforestation in 2002 (prior PPCDAM) and 2015 (PPCDAM 3rd phase), 41 and 25 municipalities, respectively. A total of 11 municipalities (orange) were present in both years, while 30 municipalities (yellow) were present only in 2002, and 14 (red) in 2015. (Sources: Prodes/INPE & MMA)

Table 2.4 – Legal Amazon deforestation average rates (km2) of listed and unlisted municipalities in four periods: prior and in the initial three phases of PPCDAm. Deforestation change between phases are represented in percentages. (Sources: Prodes/INPE & MMA)

Category	Average Deforestation (km2/year)				Deforestation change (%)			
	2002-2004 (prior PPCDAm)	2005-2008 (1st phase)	2009-2011 (2nd phase)	2012-2015 (3rd phase)	Prior-1st	1st-2nd	2nd-3rd	Prior-3rd
Unlisted	14,283	7,036	3,263	2,655	-51%	-54%	-19%	-81%
Listed	13,471	7,862	2,903	2,629	-42%	-63%	-9%	-80%

Categories of land use (land tenure)

Land tenure categories have different effects on annual deforestation rates. First, the figures reveal the strong role played by PAs and indigenous lands in halting deforestation. For instance, strict PAs have the lowest share of deforestation followed by indigenous lands and sustainable use PAs. In contrast, private lands alone were responsible for 28-46% of annual deforestation during the study period. This was closely followed by an increasing share for settlements, from 19 to 31%, between 2004 and 2014. Moreover, undesignated federal public lands are constantly subject to land grabbing and deforestation (Azevedo-Ramos and Moutinho, 2018). As a result, they attract a high share of 23-29% of deforestation over the study period (Figure 2.7 and Appendix 9.2 – Table *S* 2.1).

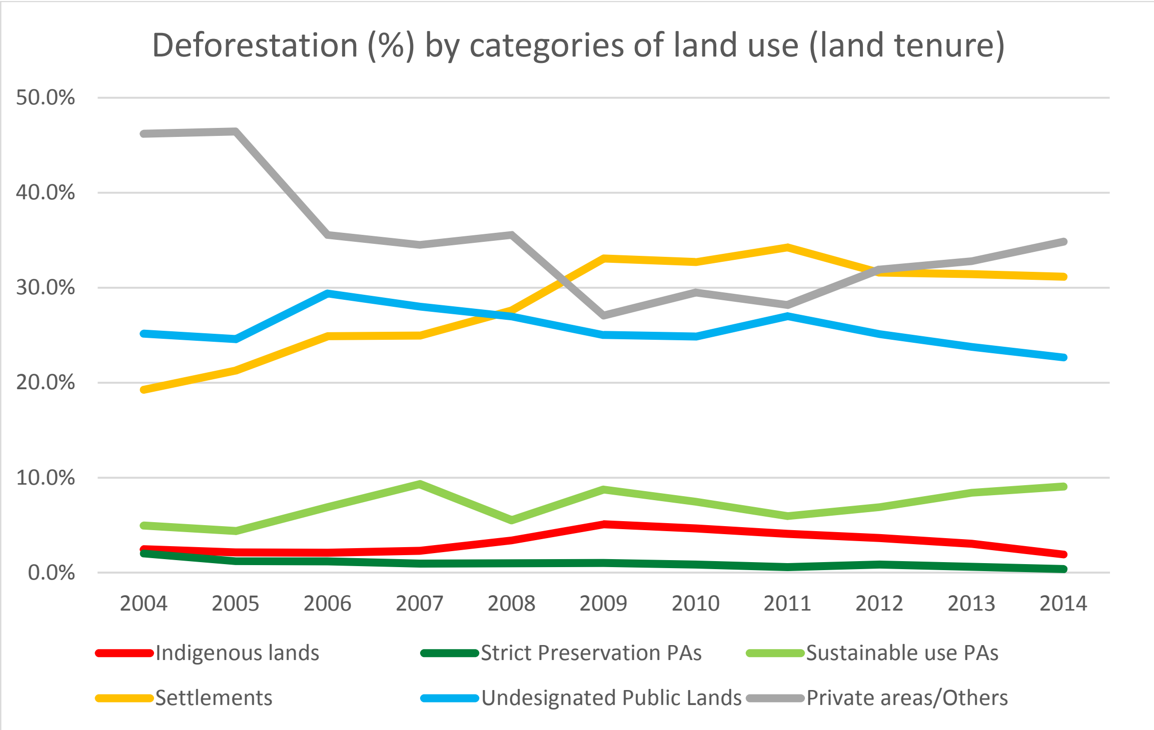


Figure 2.7 - Percentage of deforestation by categories of use in the period 2004-2014. Categories: protected areas (strict preservation and sustainable use), indigenous lands, settlements, federal public lands (without allocation), private areas and others. (Sources: MMA, FUNAI, INCRA & MDA)

Interesting trends also emerge if the land tenure categories are compared by PPCDAm phases (Table 2.5). For example, strictly protected PAs experience the lowest rates of deforestation, with a consistent downward trend from 1.5 to 0.6%. Meanwhile, private areas show a similar downward trend until the second phase, from 39.4 to 28.2%, but rates again rose to 33.2% in the third phase.

By contrast, sustainable use PAs faced an upward trend of deforestation and reached a worrying 8.1% share of forest loss in the 3rd phase. A similar trend was observed for settlements that increased their share of deforestation from 25.8 to 31.4%. In addition, Indigenous lands experience a share of 2.5-2.9%, except for the peak of 4.6% in the 2nd phase (Table 2.5).

Table 2.5 - Percentage of deforestation by categories of use prior to and during the three phases of PPCDAm's implementation. Categories: protected areas (strict preservation and sustainable use), indigenous lands, settlements, federal public lands (without allocation), private areas and others. (Sources: MMA, FUNAI, INCRA & MDA)

PPCDAm (phases)	Indigenous lands	Protected Areas		Settlements	Federal Public lands* (undesignated)	Private areas/Others
		Strict Preservation	Sustainable use			
Prior	2.5%	1.5%	5.3%	25.8%	25.5%	39.4%
1st phase	2.5%	1.1%	6.5%	24.7%	27.2%	38.0%
2nd phase	4.6%	0.8%	7.4%	33.3%	25.6%	28.2%
3rd phase	2.9%	0.6%	8.1%	31.4%	23.9%	33.2%

*Public lands exclude overlap areas with PA, IL and Settlements

The property level – CAR

CAR allows a detailed analysis of deforestation at the property level. Moreover, it is possible to disaggregate the data into the three size groups used by the Forest Code: small (<4 fiscal modules[21]); medium (4-15 fiscal modules); and large (>15 fiscal modules).

The nine states of the Legal Amazon have already registered 693,081 properties[22] that cover 2,694,720 km2. The number of properties are distributed as follows: 88% small, 8% medium and 4% large. In contrast, as expected, the occupied area shows a different pattern: 26, 15 and 58%, in small, medium and large properties, respectively. Pará supports the largest number of properties, over 202,000 properties (29% of the total). In turn, Mato Grosso has registered the largest area, of 740,000 km2 (Table 2.6).

The CAR registry includes three categories of property: private properties, settlements and traditional people and community areas. The majority of categories are private properties, but there are some overlaps between the three categories, especially in the first and second categories. So, the analysis of deforestation and land use at the property level that follows is restricted to the private properties, for simplicity and to avoid double counting.

Overall, private properties in the Amazon region were answerable for 528,781 km2 of forest loss by 2014. Together, Pará (PA) and Mato Grosso (MT) were responsible for 71%, followed by Rondônia (RO) and Maranhão (MA) with a 19% share of deforestation. Moreover, the proportion of forest loss in each property reveals that small properties are most heavily deforested with 71%, medium properties 52% and large properties 30% deforested (Table 2.7). Equally, all are above the legal requirements of the Brazilian Forest Code to set aside 80% of the property as a Legal Reserve. In special arrangements made for some settlements, the legal reserve is a collective, so small properties can use all their land area for agricultural purposes, since the Legal Reserve has been set aside in the collective Legal Reserve elsewhere. This specific case may mislead the overall interpretation of the

[21] Formally, Fiscal Module is the measurement unit in hectares determined by the National Institute for Colonization and Agrarian Reform (INCRA) for each municipality considering: i) the predominant type of rural activity: agriculture (temporary or permanent), livestock or forestry; ii) income from the predominant activity; iii) other types of activities; iv) the concept of "family property". The size of the module, can vary from 5 to 110 ha and will be specific for each municipality (Brazil, 1979). In other words, a fiscal module is defined as the minimum area needed to ensure the economic viability of exploring a rural establishment in any given Brazilian municipality.

[22] Extracted directly from the Brazilian Forest Service (SFB): http://www.florestal.gov.br/numeros-do-car (accessed on 24Sep2018)

results, because the Legal Reserve is a collective, rather than individual properties (Batistella et al., 2003).

Table 2.6 – Number and area (km2) of properties registered in CAR for the nine states of the Legal Amazon. States: Acre (AC), Amazonas (AM), Amapá (AP), Maranhão (MA), Mato Grosso (MT), Pará (PA), Rondônia (RO), Roraima (RR) and Tocacntins (TO). Property size: small, medium and large. (Source: MMA)

State	Number of properties				Properties area (km2)			
	Small	Medium	Large	Total	Small	Medium	Large	Total
AC	33,917	630	435	34,982	31,949	17,108	71,918	120,975
	97%	2%	1%		26%	14%	59%	
AP	3,442	1,367	197	5,006	8,565	14,727	19,981	43,273
	69%	27%	4%		20%	34%	46%	
AM	41,364	2,996	1,387	45,747	69,917	40,612	423,272	533,801
	90%	7%	3%		13%	8%	79%	
MA	73,778	6,108	2,382	82,268	81,670	32,338	91,393	205,401
	90%	7%	3%		40%	16%	44%	
MT	101,483	17,461	12,243	131,187	130,688	121,010	488,246	739,943
	77%	13%	9%		18%	16%	66%	
PA	180,801	14,298	7,196	202,295	250,748	94,305	344,350	689,403
	89%	7%	4%		36%	14%	50%	
RO	108,399	4,717	1,252	114,368	69,578	21,838	44,401	135,816
	95%	4%	1%		51%	16%	33%	
RR	5,655	2,106	545	8,306	17,316	20,268	11,531	49,116
	68%	25%	7%		35%	41%	23%	
TO	58,077	8,016	2,829	68,922	48,056	49,109	79,827	176,992
	84%	12%	4%		27%	28%	45%	
TOTAL	606,916	57,699	28,466	693,081	708,487	411,314	1,574,919	2,694,720
	88%	8%	4%		26%	15%	58%	

Table 2.7 – Legal Amazon deforestation accumulated up to 2014 (km2) in private properties by size (small, medium and large), and states (Acre (AC), Amazonas (AM), Amapá (AP), Maranhão (MA), Mato Grosso (MT), Pará (PA), Rondônia (RO), Roraima (RR) and Tocantins (TO)). In parenthesis, the percentage (%) of the total area of private properties deforested in each size group. (Source: MMA)

State	Private property deforestation (km2) (% of the category area deforested)			
	small	**medium**	**large**	**total**
AC	9,826 (53%)	1,351 (38%)	5,292 (14%)	16,469
AM	4,677 (40%)	1,904 (21%)	4,024 (3%)	10,605
AP	172 (25%)	155 (7%)	397 (7%)	724
MA	16,860 (87%)	7,238 (76%)	20,549 (58%)	44,647
MT	42,784 (76%)	34,495 (50%)	111,869 (31%)	189,148
PA	68,983 (69%)	41,078 (57%)	77,966 (39%)	188,026
RO	37,486 (78%)	9,053 (54%)	10,726 (36%)	57,265
RR	1,314 (44%)	996 (16%)	726 (16%)	3,036
TO	4,841 (82%)	4,767 (69%)	9,254 (51%)	18,862
Total	186,941 (71%)	101,037 (52%)	240,802 (30%)	528,781

Table 2.8 reveals a simplified version of the level of compliance with the Forest Code Legal Reserve requirements of private properties in the Legal Amazon. Overall, only 8, 23 and 36% of small, medium and large properties are in compliance, respectively. Regarding the small property category, Amapá has the largest share of compliance with 48%, while Amazonas is second with 30%. At the other end of the spectrum, Maranhão, Tocantins, Mato Grosso and Rondônia each have over 70% of the small property category with more than 80% of the property deforested, far beyond the 20% threshold.

The scenario for the medium property category is slightly better. Three states have over 60% compliance based on the conditions of a Legal Reserve. Again Amapá shows the strongest compliance, 86%, followed by Amazonas and Roraima with more than 60%. In contrast, Maranhão and Tocantins have the largest share of deforested properties with over 80% deforested, at 64 and 58%, respectively.

For the category of large properties, four states lie above the 50% compliance: Amapá (90), Amazonas (79), Roraima (67) and Acre (52). By contrast, Maranhão and Tocantins, as in the other categories, remain with the highest shares of properties over 80% deforested, at 46%.

Table 2.8 – Percentage of private property area deforested accumulated up to 2014, categorized by states and size. States: Acre (AC), Amazonas (AM), Amapá (AP), Maranhão (MA), Mato Grosso (MT), Pará (PA), Rondônia (RO), Roraima (RR) and Tocacntins (TO). Properties size: small, medium and large. (Sources: Prodes/INPE & MMA)

Property size	Percentage deforested	AC	AM	AP	MA	MT	PA	RO	RR	TO	Total
Small	<20%	13%	30%	48%	4%	5%	8%	3%	17%	7%	8%
	21-50%	21%	30%	29%	6%	7%	16%	8%	42%	8%	13%
	51-80%	28%	19%	14%	11%	18%	23%	21%	30%	9%	21%
	>80%	37%	22%	9%	79%	70%	53%	69%	11%	76%	59%
Medium	<20%	40%	61%	86%	11%	26%	15%	16%	66%	17%	23%
	21-50%	25%	24%	11%	9%	19%	22%	24%	25%	10%	20%
	51-80%	21%	11%	2%	16%	28%	26%	34%	8%	14%	25%
	>80%	13%	4%	1%	64%	27%	37%	26%	2%	58%	32%
Large	<20%	52%	79%	90%	20%	40%	28%	23%	67%	30%	36%
	21-50%	29%	15%	10%	14%	25%	24%	28%	24%	11%	24%
	51-80%	16%	4%	0%	20%	23%	26%	34%	8%	13%	23%
	>80%	4%	1%	0%	46%	13%	22%	15%	1%	46%	18%

2.2 Characterization of land use and land cover change in the Brazilian Amazon at different scales

This section presents post-deforestation land uses, but is restricted to years when the mappings were available: 2004, 2008, 2010, 2012 and 2014[23] (Inpe and Embrapa, 2016).

By 2014, the Brazilian Legal Amazon had accumulated over 762,000 km2 of forest loss, or 15.2% of its surface, compared with 614,000 km2 (12.5%) in 2004 (Table 2.9). Due to the implementation of PPCDAm, the proportion of area lost annually decreased from 0.6 to 0.1% during 2004 to 2014. However, overall forest loss in the Amazon still remained high, at 148,536 km2 from 2004 to 2014. In turn, this represents almost 4% of the Brazilian Amazon forests (Table 2.10).

Overall, the land uses have similar distributions over the five mappings, between 2004 and 2014, but with some categories presenting specific trends. For example, the three most representative categories: pasture, secondary vegetation and agriculture, cover over 80% of the area mapped.

First, pastures[24] are the dominant land use in the Amazon, and cover over 60% of its surface. Surprisingly, secondary vegetation is the next most dominant category of land use with 23% by 2014, compared to 16% in 2004. Annual crops[25], the third category of importance, have almost doubled their share, from 3 to 6%, a growth of 27,000 km2 from 2004 to 2014 (Table 2.9 and Figure 2.8).

The land use transition matrix (Table 2.10) reveals that 44% (64,616 km2) of forest losses were replaced by pasture, while 5% (7,665 km2) was converted to annual crops, and 18% (25,367 km2) remained as natural regeneration. Besides, 68% of pastures persisted from 2004 to 2014, 14% resulted from forest conversion and only 0.3% came from conversion of annual crops. By contrast, crops persisted in 37% out of 45,050 km2. Even more interestingly, 40% of the area resulted from pasture and another 17% from forest conversion. Moreover, 57,917 km2 of pastures were abandoned and re-categorized as natural regeneration, a 33% contribution to the 173,387 km2 of natural regeneration observed in 2014. In addition, 15% of natural regeneration came from forests and 34% has persisted since 2004.

[23] Two additional maps (1991 and 2000) were released after the analysis of this work was completed.
[24] Includes four Terraclass categories: herbaceous pasture, pasture with exposed soil, shrubby pasture and regeneration with pasture.
[25] Perennial cultures were not assessed by Terraclass and thence omitted of all analyses.

Table 2.9 – Land use and land cover thematic categories mapped by Terraclass, for five dates (2004, 2008, 2010, 2012 and 2014), in km2 and (%). The first column represents thematic categories aggregation. For description and details of thematic categories see Appendix 0. (Source: adapted from Inpe and Embrapa (2016)).

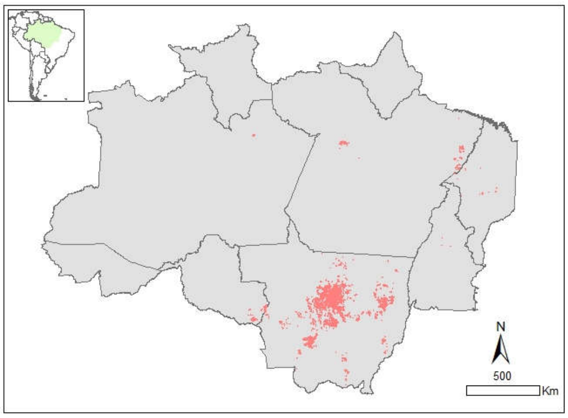
Thematic Group	Thematic category*	Area km² (%)				
		2004	2008	2010	2012	2014
A	Annual crops	18,354 (3.0)	34,927 (4.9)	39,978 (5.4)	42,346 (5.6)	45,050 (5.9)
Z	Non-observed areas	48,566 (7.9)	45,406 (6.4)	45,849 (6.2)	69,132 (9.2)	30,056 (4.0)
U	Urban areas (u)	2,579 (0.4)	3,818 (0.5)	4,474 (0.6)	5,341 (0.7)	6,010 (0.8)
	Mining (u)	799 (0.1)	731 (0.1)	967 (0.1)	1,049 (0.1)	1,272 (0.2)
	Mosaic of uses (u)	16,284 (2.7)	24,417 (3.4)	17,963 (2.4)	9,590 (1.3)	16,256 (2.1)
X	Others	4,637 (0.8)	478 (0.1)	2,731 (0.4)	6,113 (0.8)	7,752 (1.0)
C	Pasture (clean pasture)	306,039 (49.8)	335,715 (47.4)	339,852 (45.9)	345,420 (46.0)	377,470 (49.6)
P	Pasture with exposed soil (p)	106 (0.0)	594 (0.1)	373 (0.1)	43 (0.0)	63 (0.0)
	Shrubby (dirty) pasture (p)	55,250 (9.0)	62,824 (8.9)	56,077 (7.6)	50,472 (6.7)	60,199 (7.9)
	Regeneration with pasture (p)	60,641 (9.9)	48,027 (6.8)	63,165 (8.5)	46,468 (6.2)	42,028 (5.5)
R	Reforestation**	0 (0.0)	0 (0.0)	3,015 (0.4)	3,176 (0.4)	2,922 (0.4)
S	Secondary vegetation	100,674 (16.4)	150,815 (21.3)	165,229 (22.3)	172,190 (22.9)	173,387 (22.8)
	Total	613,928 (100)	707,752 (100)	739,673 (100)	751,340 (100)	762,464 (100)

*Detailed description of each class can be found in Almeida et al. (2016) adapted in Appendix 9.2 – Table *S* 2.2
** Reforestation mapping started only in 2010.

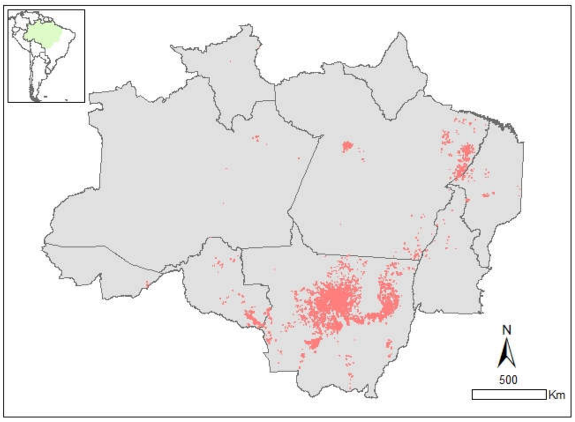
Another interesting perspective of land use comes from its evaluation in 2014, based on the year in which the area was cleared (Figure 2.9). First, annual crops mostly occupied areas cleared before 2006, in line with the findings of Macedo et al. (2012). In turn, this observation is probably related to the soy moratorium. For instance, it responds for 14% (3,517 km2) of 2004 deforested areas and only 0.01% (50km2) of areas cleared in 2013. In further turn, both clean and dirty pasture had the largest share of occupation between 61 and 77%, during the same period. The natural regeneration and secondary vegetation has played an important role, with 18% (922 km2) of 2013 cleared areas, reaching 28% (1,670 km2) in 2010 and stabilizing around 20% for the initial period of PPCDAm, 2004-2007.

Crops

2004

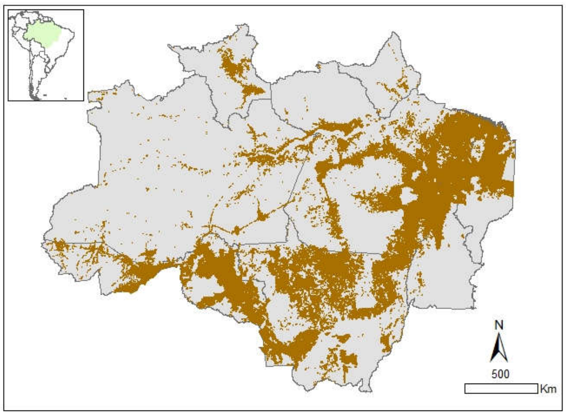


2014

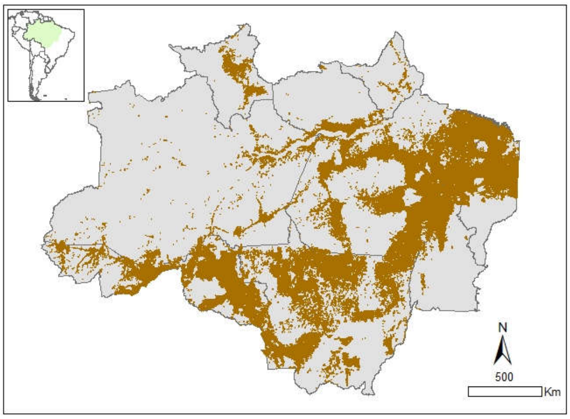


Pasture

2004

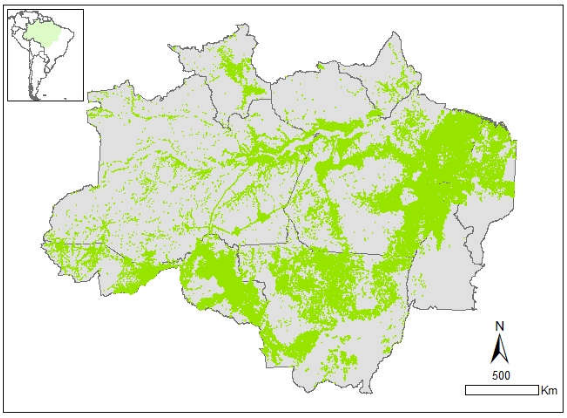


2014



Natural regeneration/Secondary vegetation

2004



2014

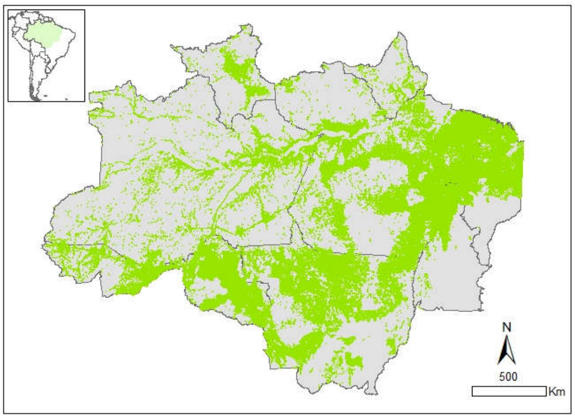


Figure 2.8 – Distribution/Area occupied by crops, pasture and natural regeneration in 2004 and 2014. Source: Terraclass (Inpe and Embrapa, 2016).

Table 2.10 – Land use and land cover transition matrix between 2004-2014 (km2). (Source: adapted from Inpe and Embrapa (2016))

		2014						
	Categories	Forest	Annual crop	Pasture	Secondary Vegetation	Others	Total	Losses
2004	Forest	3,139,392	7,665	64,616	25,367	49,089	3,287,928	148,536
	Annual crop		16,504	1,585	150	115	18,354	1,850
	Pasture		17,794	323,957	57,917	24,048	423,716	99,759
	Secondary Vegetation		1,884	28,488	58,634	11,668	100,674	42,040
	Others		1,203	61,114	31,318	14,368	116,344	101,976
	Total	3,139,392	45,050	479,760	173,387	99,288	3,947,016	
	Gains	-	28,546	155,803	114,753	84,920		
	Balance	-148,536	26,696	56,044	72,713	-17,056		

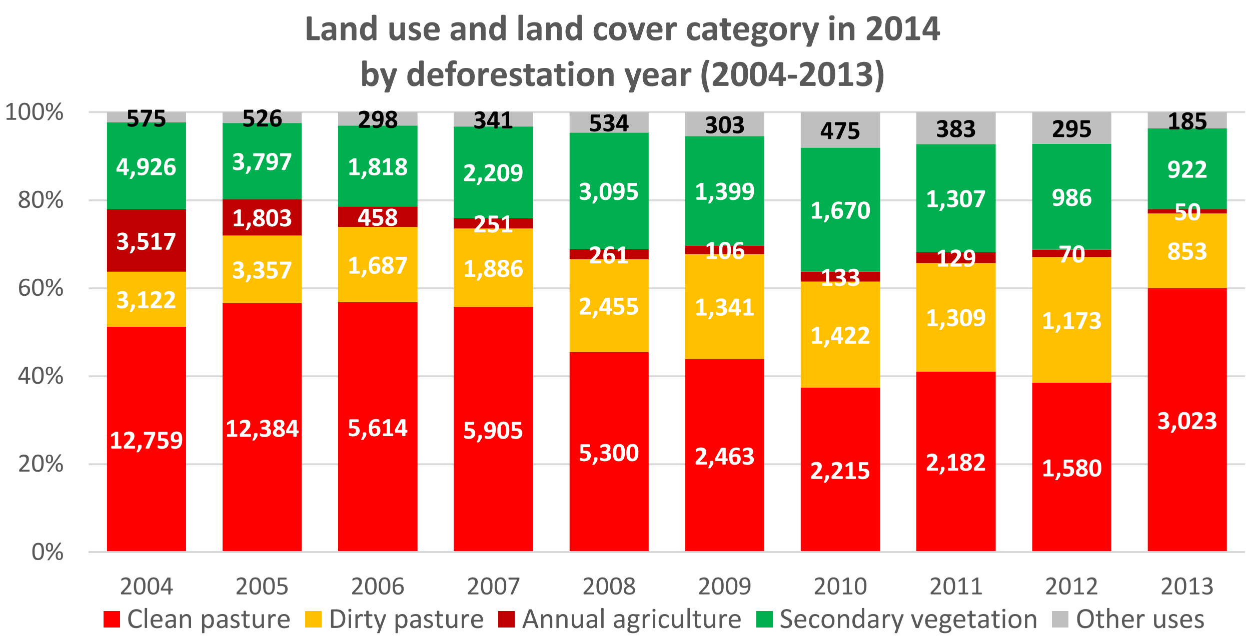


Figure 2.9 – Evaluation of 2014 land use and land cover of the more representative thematic categories (annual crops, pastures: clean and dirty, secondary vegetation and forest) on deforested areas from 2004 to 2013. (Sources: Prodes/INPE & Terraclass (INPE-EMBRAPA))

Land use and land cover change at the property level (CAR)[26]

Land use at the property level increased from 545,312 km2 in 2004 to 657,852 km2 in 2014 (Figure 2.10 and Table 2.11). First, there is a noticeable increasing trend for annual crops during the study period, independent of property size. This trend was more pronounced in large properties, 4.1% in 2014, with almost three times the area compared to 2004. The same can be observed for small properties but at a smaller scale of only 1.4% of land use, reaching 9,497 km2 in 2014, and equivalent to the initial value for large properties in 2004.

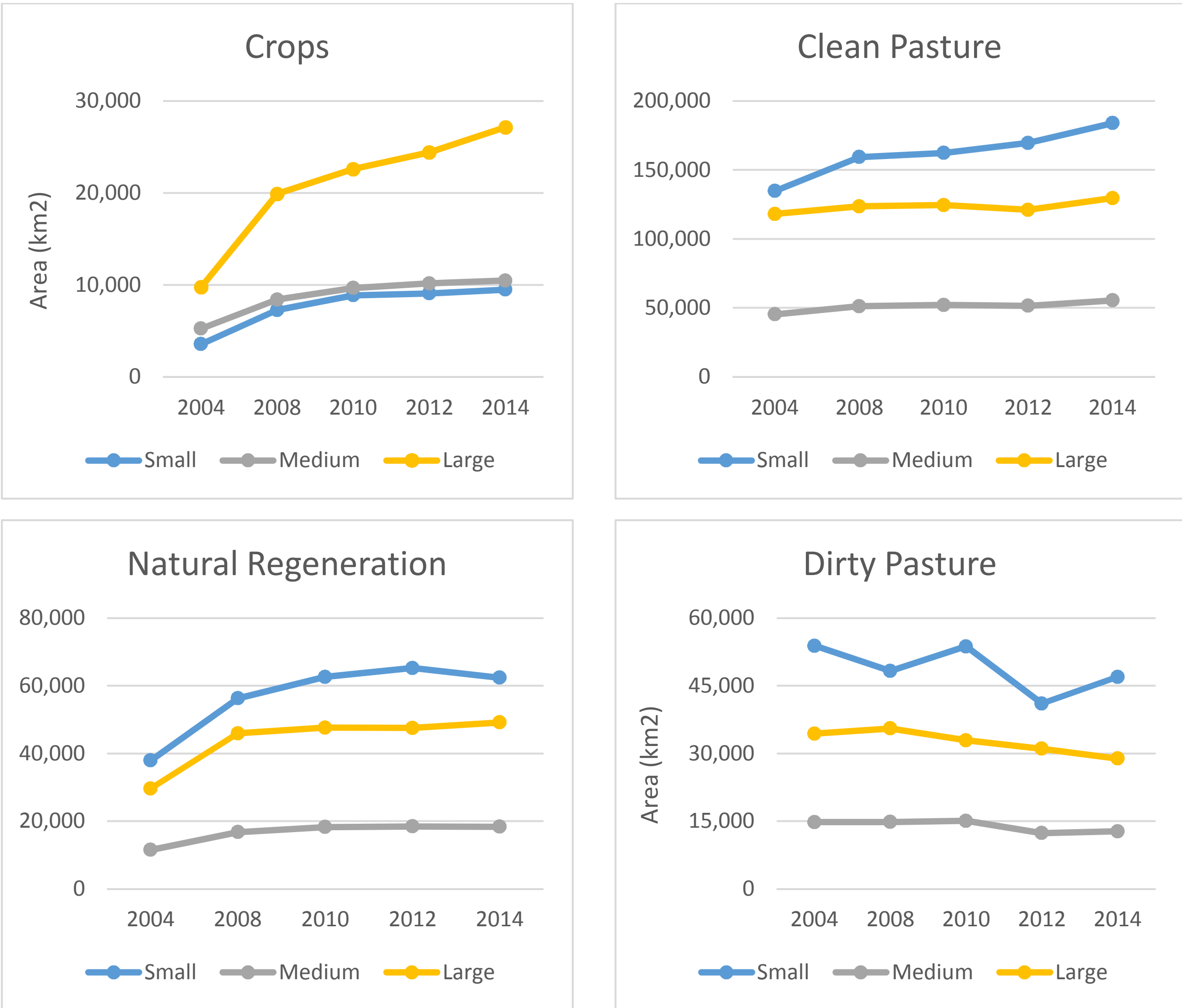


Figure 2.10 - Land use of the most representative thematic categories: annual crops, pastures: clean and dirty, secondary vegetation (km2). Mapped at the property level according to the three sizes of the Forest Code: small, medium and large. (Sources: MMA & Terraclass(INPE-EMBRAPA))

[26] Land use at the property level (small, medium and large) by states is available in Appendix 9.2 – Table *S* 2.2.

Table 2.11 – Land use and land cover of the more representative thematic categories: annual crops, pastures: clean and dirty, secondary vegetation, in km2, mapped at the property level according to the forest code three size categories: small, medium and large. (Sources: MMA & Terraclass(INPE-EMBRAPA))

Thematic category	Property size	2004	2008	2010	2012	2014
Crops	small	3,553 (0.7%)	7,270 (1.2%)	8,867 (1.4%)	9,084 (1.5%)	9,497 (1.4%)
	medium	5,252 (1.0%)	8,412 (1.4%)	9,667 (1.5%)	10,167 (1.6%)	10,468 (1.6%)
	large	9,751 (1.8%)	19,887 (3.2%)	22,597 (3.6%)	24,415 (3.9%)	27,152 (4.1%)
Clean Pasture	small	134,769 (24.7%)	159,418 (25.9%)	162,373 (25.7%)	169,598 (27.4%)	183,950 (28.0%)
	medium	45,292 (8.3%)	51,177 (8.3%)	52,093 (8.2%)	51,532 (8.3%)	55,463 (8.4%)
	large	118,061 (21.7%)	123,670 (20.1%)	124,495 (19.7%)	121,077 (19.6%)	129,609 (19.7%)
Dirty pasture	small	53,859 (9.9%)	48,286 (7.8%)	53,711 (8.5%)	41,067 (6.6%)	46,995 (7.1%)
	medium	14,777 (2.7%)	14,813 (2.4%)	15,073 (2.4%)	12,366 (2.0%)	12,733 (1.9%)
	large	34,413 (6.3%)	35,547 (5.8%)	32,918 (5.2%)	31,051 (5.0%)	28,885 (4.4%)
Secondary Vegetation	small	37,956 (7.0%)	56,320 (9.2%)	62,646 (9.9%)	65,278 (10.5%)	62,379 (9.5%)
	medium	11,498 (2.1%)	16,785 (2.7%)	18,274 (2.9%)	18,431 (3.0%)	18,354 (2.8%)
	large	29,647 (5.4%)	45,968 (7.5%)	47,626 (7.5%)	47,548 (7.7%)	49,182 (7.5%)
Other uses	small	25,367 (4.7%)	17,535 (2.9%)	14,376 (2.3%)	9,767 (1.6%)	13,534 (2.1%)
	medium	6,544 (1.2%)	2,886 (0.5%)	1,841 (0.3%)	1,745 (0.3%)	2,238 (0.3%)
	large	14,575 (2.7%)	7,229 (1.2%)	6,081 (1.0%)	5,657 (0.9%)	7,414 (1.1%)
	Total	545,312 (100%)	615,201 (100%)	632,638 (100%)	618,784 (100%)	657,852 (100%)

Second, as expected, clean pasture is the dominant land use category for all sizes of properties, but each shows different trends. Small properties have increased their areas of pasture by 27% and also their share of land use from 24.7% (2004) to 28% (2014). In turn, large properties have expanded by only 9%, but with a declining trend from 21.7 to 19.7% between 2004 and 2014. Dirty pasture has a declining share in land use in all property sizes, while the largest portions are in small properties.

Third, natural regeneration has had an increasing share until 2012, followed by a slight decline in 2014 for all property sizes. In small, medium and large properties the area increased by 40%, but at different scales, reaching 62,379 km2, 18,354 km2 and 49,182 km2, respectively, in 2014.

I have now set the scene for the study, by providing relevant background information on global climate change, the importance of the Brazilian Amazon, patterns of deforestation, and early efforts to conserve the forest from land use change. I will now move to describing the general methods used in this study.

3 Data and methods

3.1 Data

This study was set in a situation of great complexity, as Chapters 1 and 2 have shown. Nevertheless, the study is mostly based on freely accessible datasets from the Brazilian Government, available on the web (Appendix 9.1). Five datasets and their respective institutions were critical to the development and outcome of this study: Brazilian Environment Agency (Ibama); National Institute for Space Research (Inpe); Brazilian Forest Service (SFB); Brazilian Institute of Geography and Statistics (IBGE); and the Brazilian Central Bank. At the start of the study in 2016, as much as possible of the available data were collected to cover the study period 2004-2014, and updated whenever necessary. The period coincides with the start of PPCDAm and the first and last years of land use change maps of TerraClass. It is important to highlight that the analyses based on the above mentioned public databases show variable levels of uncertainty, but still provide the best available information to draw out trends and provide the necessary knowledge for the critical analysis that this thesis seeks to undertake.

Ibama's law enforcement dataset has detailed information of fines and embargoed areas, as a subset of the fines data, and this was updated on a daily basis (Table 3.1). Since 2004, the spatial information has improved significantly in quality and quantity. Therefore, more accurate spatial information is available for a growing number of fines and embargoes that have built up on the web in recent years.

Table 3.1 Number of fines for the nine states of the Brazilian Legal Amazon: Acre (AC), Amazonas (AM), Amapá (AP), Maranhão (MA), Mato Grosso (MT), Pará(PA), Rondônia (RO), Roraima (RR) and Tocantins(TO). Source: Ibama

Year/States	AC	AM	AP	MA	MT	PA	RO	RR	TO	Total
2002	153	277	38	379	1,748	1,429	738	128	846	5,736
2003	253	485	53	362	1,630	2,162	811	197	298	6,251
2004	236	456	121	231	1,999	1,501	1,435	152	290	6,421
2005	335	581	242	687	1,943	2,486	1,741	416	402	8,833
2006	294	457	219	878	1,479	1,958	1,617	397	213	7,512
2007	948	724	135	913	1,742	1,890	1,692	84	405	8,533
2008	342	602	158	587	1,784	2,529	2,128	232	369	8,731
2009	411	386	122	556	964	1,796	1,299	335	379	6,248
2010	175	397	119	851	1,576	2,033	1,578	215	243	7,187
2011	185	407	105	330	1,368	1,759	1,190	272	264	5,880
2012	80	370	37	474	1,171	1,551	769	310	274	5,036
2013	131	379	32	354	1,158	1,497	970	169	216	4,906
2014	147	471	25	188	1,190	1,805	777	127	233	4,963
2015	129	421	350	173	1,124	1,938	1,189	250	317	5,891
2016	286	415	70	300	1,025	1,444	1,299	179	112	5,130
Total	4,105	6,828	1,826	7,263	21,901	27,778	19,233	3,463	4,861	97,258

Inpe's database of deforestation holds high resolution information of Amazon deforestation and land use change, included in Prodes and TerraClass programmes, respectively. In addition, Inpe holds the AMBDATA[27], a comprehensive database of environmental variables for species distribution modelling, that gathered data from different official sources.

Deforestation is measured annually with a minimum detectable area of 6.25ha[28](Camara et al., 2006; Inpe, 2017) (Table 2.2). TerraClass is a more recent programme and has already delivered seven land use maps for the Amazon (Table 2.9)(Almeida et al., 2016). This study will consider the three most representative land uses: agriculture (6%), pastures (63%) and secondary vegetation (23%), in the 2014 mapping. The first two are well described in the literature as the main drivers of deforestation in the Amazon region during the last 50 years (Fearnside, 1983; Hecht, 1992; Moran, 1993; Walker et al., 2000; Nepstad et al., 2006; Aguiar et al., 2007; Fearnside et al., 2013). For simplicity, the four pasture categories will be grouped in two classes[29]: clean pasture (c) – herbaceous pasture; and dirty pasture (p) includes the remaining three categories - shrubby pasture, pasture with exposed soil and regeneration with pasture. Finds of secondary vegetation, the third land use category, in the literature include two main possibilities: permanent land or temporarily abandoned land (Laue and Arima, 2014). The former suggests an ongoing restoration process and the latter could be part of a fallow period in the land use cycle that might last for as long as decades, until it is again cleared (Moran and Brondizio, 1998; Moran et al., 2000; Bowen et al., 2007; Nunes et al., 2015; Paula et al., 2017).

The Brazilian Forest Service holds the spatial environmental registry system for all rural properties (SICAR) across the national territory. This is a requirement of the new Forest Code Law 12,651 and CAR regulation decree 7,830 enacted in 2012 (Brazil, 2012a; Brazil, 2012b), with the intention of enforcing and monitoring compliance with environmental law. So far, the Legal Amazon states have already registered close to 235million ha and more than 1 million properties (Brazil, 2018) (Table 3.2). Every property with an entry recorded in the system includes spatial information about their limits, legal reserve, permanent preservation areas and productive area.

The CAR registry is based on an electronic self-declaration system on the part of the property owner who uploaded to the system (SICAR). Thus, after registration in the CAR database, validation is

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[27] Environmental dataset for modelling species distribution (http://www.dpi.inpe.br/Ambdata/index.php)

[28] This is to keep consistency along the time series that started with manual mapping on paper, in which the area of 1x1mm represented 6.25ha. Details can be found at the PRODES program webpage and documentation. (http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes)

[29] This grouping will clearly separate out the most active pasture (c) from the least active (p). Also, it will simplify the analysis of over 36M land use polygons.

carried out by state environmental agencies, resulting in two routes for property owners to follow: 1) ACTIVE: when owners fulfil all of the requirements; and 2) STAND-BY: when owners do not fulfil all the requirements. In the latter scenario, the landowner requires a plan for restoring degraded areas (PRA in Portuguese), be committed to resolving environmental liabilities such as Legal Reserve (LR) or Permanent Preservation Areas (PPA) deficits. In turn, the CAR can become ACTIVE. Relevant information is open to the public for downloading on the Forest Service website, a powerful tool allowing consumers, industry and banks to identify deforestation and illegality on each of the properties to which they are related.

Table 3.2 – Summary of the environmental rural registry (CAR) for the nine states of the Legal Amazon: area (ha) and number of properties (accessed on 24Sep2018). (Source: MMA)

UF	State	Registered area (ha)	Number of registered properties
AC	Acre	9,466,751	49,436
AP	Amapá	3,389,535	13,798
AM	Amazonas	31,226,115	78,804
MA	Maranhão	20,227,118	182,904
MT	Mato Grosso	73,383,593	196,676
PA	Pará	60,929,655	329,872
RO	Rondônia	12,532,260	135,993
RR	Roraima	4,837,399	22,416
TO	Tocantins	17,247,100	84,907
	Sub-Total	233,239,526	1,094,806
	BRAZIL	463,133,803	5,321,742

IBGE statistical database holds all the baseline economic and social data needed for this research. The organization is responsible for producing most of the official statistics and indicators of the Brazilian Government. For instance, IBGE is responsible for: the agricultural census; demographic census; and annual production by municipalities of: agriculture; livestock; and, timber; monthly economic indicators; political borders (national, states and municipalities); Legal Amazon boundaries; biomes and ecosystems borders; and so on (see Appendix 9.1).

Finally, **the Brazilian Central Bank** holds data on all the loans and subsidies given by all Brazilian banks for agriculture and livestock development (Table 3.3). All information is available yearly at the municipality level (Figure 3.1).

Table 3.3 – Summary of agricultural loans (2004-2014) for the nine states of the Legal Amazon: Acre (AC), Amazonas (AM), Amapá (AP), Maranhão (MA), Mato Grosso (MT), Pará(PA), Rondônia (RO), Roraima (RR) and Tocantins(TO). Source: Brazilian Central Bank

	Agriculture		Livestock		Total	
State	Value* (millions R$)	Number of contracts (thousands)	Value* (millions R$)	Number of contracts (thousands)	Value* (millions R$)	Number of contracts (thousands)
AC	440	44	1,638	51	2,078	95
AM	981	87	1,114	54	2,095	140
AP	146	10	86	5	232	14
MA	10,075	465	8,072	932	18,147	1,397
MT	65,030	166	29,114	324	94,144	490
PA	3,810	221	10,925	379	14,735	600
RO	2,705	87	9,389	212	12,094	299
RR	335	12	530	18	865	30
TO	7,850	62	11,178	207	19,028	269
Total	91,373	1,153	72,046	2,181	163,419	3,334

* Values deflated to June 2016 in Brazilian Reais (R$) using the General Prices Index (IGP-M, Brazilian acronym)

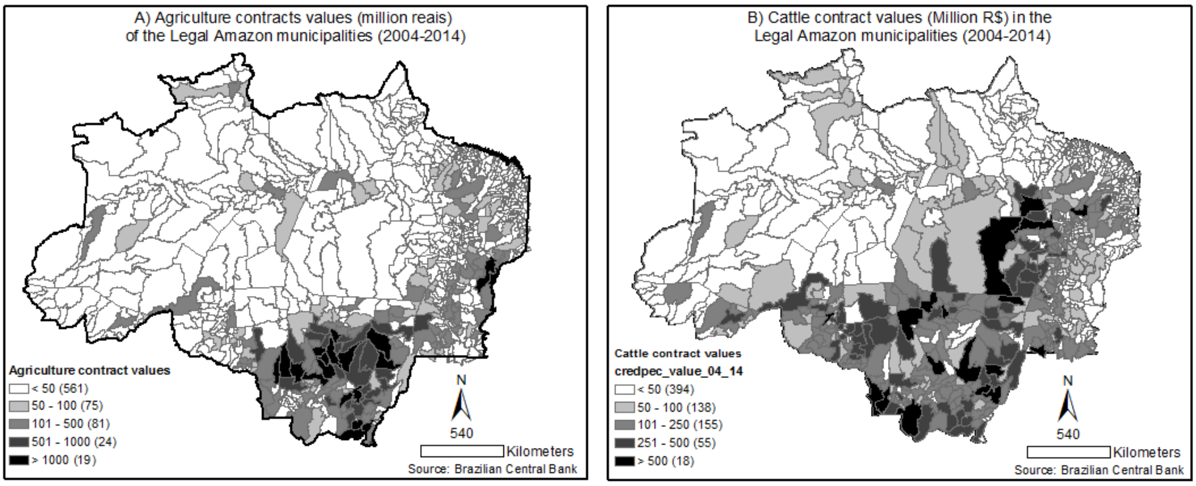

Figure 3.1 - Brazilian Central Bank agriculture (A) and cattle (B) loans value (x R$ 1,000,000) in the Legal Amazon accumulated in the study period 2004-2014.(Source: Brazilian Central Bank)

3.2 Methods

I used two distinct techniques to investigate the possible influence of law enforcement operations in the field on deforestation (Chapter 4); on land use change (Chapter 5); and, on persistence of natural regeneration (Chapter 6).

The first technique applied a quasi-experimental design with a spatial autoregressive model with a cross-sectional approach to data on deforestation and persistence of natural regeneration. The second technique used was a Difference-in-differences with entropy balance to answer the question of land use change. Data availability helped define the appropriate method to answer the three major lines of enquiry of this study. All statistical analyses were performed in STATA 15.1. The following paragraphs will provide details of how the two techniques were implemented.

First, in Chapters 4 and 6, the analyses drew on the cross-sectional methodological approach, to address whether environmental law enforcement, alone or in combination with other drivers, may have influence over rates of deforestation (Chapter 4), and over the persistence of natural regeneration (Chapter 6) in the Brazilian Amazon. The analyses covered the period 2004-2014, to shed light on the possible influence of law enforcement. Thus, I proceeded with the following steps: data collection and preparation, selection of variables, analysis and hypothesis testing.

The initial step consisted of collecting, preparing and organizing all the available spatial and non-spatial information. Therefore, the appropriate data from the databases (Appendix 9.1) were organized in a ArcGIS 10.4 geodatabase environment, and their consistency checked. All non-spatial data were integrated into the geodatabase using the Brazilian official municipality codes as the reference for reducing the information of the 772 municipalities into a data set suitable for this specific study. After completing this step, all datasets were organized and made ready for use in selecting the appropriate variables for the analysis.

Firstly, I sought an appropriate group of variables by searching the literature for their possible relationhip to, or influence on, deforestation and/or the persistence of natural regeneration. The suggested list of variables includes: policy-related variables to combat deforestation: fines and embargoed areas (Becker, 1968; Gratwicke, 2007; Iglesias et al., 2012; Schmitt, 2015; Schmitt and Scardua, 2015); federal government priority list of municipalities (Alix-Garcia et al., 2017); land use designation: protected areas, indigenous lands and settlements (Soares-Filho et al., 2010; Aldrich et al., 2012; Alencar et al., 2016); farm characteristics (Perz and Skole, 2003b): share of properties with CAR (Alix-Garcia et al., 2017); socio-economic: population density, rural population density, in-migrants (Moran et al., 2000; Perz and Skole, 2003b; Ludewigs et al., 2009; Mills Busa, 2013; Wortley et al., 2013), values of subsidized credits for crops and livestock (Hargrave and Kis-Katos, 2013; Assunção et al., 2015; Cisneros et al., 2015); non-traditional land use (Perz and Skole, 2003b): soy area, heads of cattle, logging/forestry, persistent area of agriculture and clean pasture (Fearnside, 1983; Kaimowitz, 2002; Arima et al., 2011; Bowman et al., 2012; Latawiec et al., 2015), regular technical assistance (Alencar et al., 2016), number of companies, land value (Hecht, 1985; Alston et al., 1995; Merry et al., 2008; Bowman et al., 2012; Hargrave and Kis-Katos, 2013), income unequality (Gini index), GDP; municipality area; acessibility: roads/highways and roads/highways junctions (Pfaff, 1999; Laurance et al., 2002; Soares-Filho et al., 2004; Fearnside and de Alencastro Graça, 2006; Perz et al., 2007; Pfaff et al., 2007; Hargrave and Kis-Katos, 2013; Arima, 2016); and enviromental/biophysical conditions: rainfall, temperature, fires, slope and non-forest areas (Kuhlman, 2005; Aguiar et al., 2007; van Marle et al., 2017). Then, the presumably relevant variables were checked for multicollinearity in order to proceed to the next step with only the most appropriate and least inter-correlated variables.

As good practice to avoid multicollinearity (Kutner et al., 2004), all correlation coefficients above 0.65 were identified to prevent the use of these variables simultaneously. The assumption of no severe multicollinearity was examined using variance inflation factor (VIF) values below 5.0, the threshold value suggested by Studenmund (2014) for severe multicollinearity.

The next step was the cross-sectional analysis, in a standard specific to general approach (Elhorst, 2010; Golgher and Voss, 2016). Therefore, the analysis started with a non-spatial linear regression model (OLS) as a reference, with the assumption that observations are independent and do not suffer from spatial inter-dependence. As a non-spatial model, this approach is commonly used as a diagnostic tool for the evaluation of the model specifications, and as a benchmark for comparisons with spatial models. Next, the Moran and Breusch-Pagan tests were applied to check for spatial auto-correlation and heteroscedasticity, respectively.

Tobler's First Law of Geography (Tobler 1970) states: 'Everything is related to everything else, but near things are more related than distant things.' Therefore, once the OLS was rejected, and before moving to the spatial models analysis, the spatial weight matrix (W) was created. In this case, the spatial weight matrix was based on the inverse distance of the centroids of the municipalities (row standardized to 1) was more appropriate due to considerable differences in size and shape of the Amazon municipalities.

Next the three spatial models, named spatial error model (SEM), spatial lag model (SAR) and their combination, the Kelejian-Prucha model (SAC), were estimated. Subsequently, I runned a test to reject the more restricted models: SAR or SEM, in favour of the combined model (SAC). Thus, it was possible to identify what model best described the data.

Formally, in cross-section data analysis, the four models are calculated as:

OLS:	$Y = \beta E + X\beta + \varepsilon$		
SAR:	$Y = \rho W Y + \beta E + X\beta + \varepsilon$		$\rho \neq 0$
SEM:	$Y = \beta E + X\beta + u$	$u = \lambda W u + \varepsilon$	$\lambda \neq 0$
SAC:	$Y = \rho W Y + \beta E + X\beta + u$	$u = \lambda W u + \varepsilon$	$\rho \neq 0$ and $\lambda \neq 0$

Where:

Y is the persistent natural regeneration or deforestation
E is the enforcement variable (number of fines)
X the matrix of control variables
β the corresponding parameter vectors of E & X
ε no spatial-dependent error
ρ is the autoregressive spatial scalar in Y
λ is the autoregressive spatial scalar in u
W the spatial-weighting matrix
u spatial-dependent error.

In contrast to the first approach that considered the full period 2004-2014 of PPCDAm in a cross section analysis, the second approach considered the priority list policy (see Section 3.2.1), which led to law enforcement intensification on this priority group of municipalities with high rates of deforestation, also known as the “black list”. This official act of the Brazilian government consolidated deforestation hotspots where the law enforcement has been intensifying its actions since 2005 (Figure 3.2).

In this case, I assessed the possible influence of law enforcement on land use and land cover change (Chapter 5) by comparing listed (treatment) and non-listed (control) municipalities before and after the first priority list had been released in early 2008. The analyses of land use and land cover change were also performed at the property level: small and medium-large, and settlements. The following paragraphs will describe the two major steps of this approach and explain the priority list criteria.

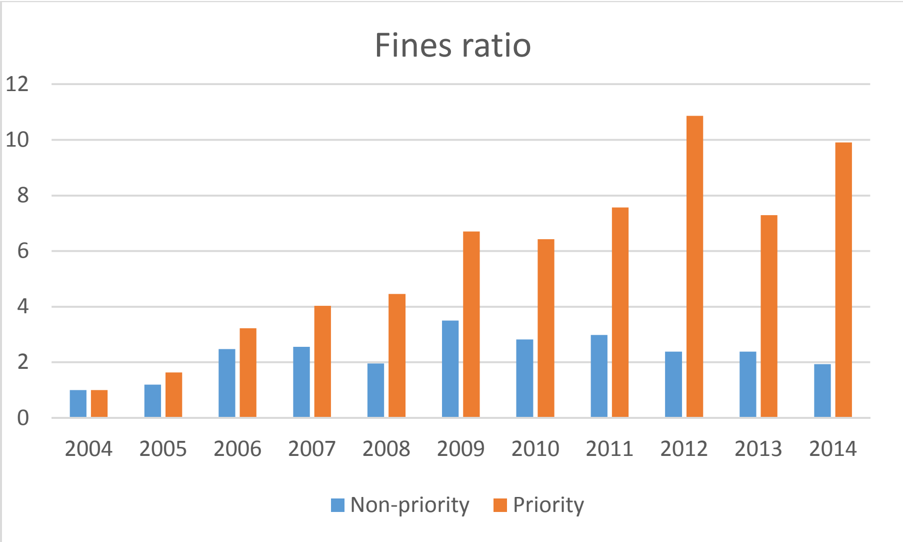

Figure 3.2 – Ratio of the number of fines per km2 deforested for priority (P) and non-priority (NP) municipalities in the Brazilian Amazon. Figures are restricted to 494 municipalities with >10% forest cover in 2004, Source: MMA & Terraclass.

In order to explore possible causal inferences (Holland, 1986), I built a reasonable counterfactual for land use and land cover change, and socio-economic indicators trends of the priority municipalities in case they were not listed. Consequently, I applied a quasi-experimental research design In Chapter 5. This technique has recently emerged as an important tool in other areas of knowledge like health, combining Difference-in-Differences with entropy balancing (Hainmueller, 2012). The technique has been progressively used in land system science (Meyfroidt et al., 2014), and assessments of conservation success (Ferraro et al., 2007; Ferraro, 2009).

This approach started with the selection of a control group, out of the non-listed municipalities, based on observable characteristics pre-treatment (2008) that are relevant and may have influenced the outcome variables. The idea behind this adjustment technique is to balance covariates to restrict the analysis to comparable municipalities. Therefore, the control group is constructed by a synthetic control method. The maximum entropy reweighting technique was proposed by Hainmueller (2012). This emerging procedure is straightforward to implement and focus directly on balancing covariates, assigning weights to each of the non-listed municipalities (control) such that the reweighted data are nearly the same of the specified moment conditions (first order: means and/or higher-ordered moments: variances and skewness) of the priority list (treated group). In this case, the first moment of the covariates, namely the mean, of treated and control groups is balanced, unless otherwise noted.

Hainmueller (2012) highlights advantages in adopting this procedure in observational studies. Most importantly, entropy balance increases balance quality, since the weights are directly adjusted to known sample moments, eliminating covariate unbalance more efficiently, thus, performing better than conventional matching techniques (Zhao and Percival, 2015; Parish et al., 2017; Koch et al., 2019). A second advantage is that the reweighting method also retains valuable information by allowing the unit weights to vary smoothly, while units are either discarded or matched with nearest neighbour matching technique. Third, this pre-processing technique is versatile and the resulting balance can be easily applied to almost any standard estimator for the subsequent estimation of treatment effects. In summary, these balance improvements can reduce model dependence for the subsequent estimation of treatment effects. However, I had to consider that unobserved factors could not be accounted for in the reweighting approach. Only the measured covariates are controlled for, and any omitted factors can result in biased impact estimates (Parish et al., 2017).

I implemented the entropy balancing pre-processing approach using the ebalance package for Stata (Hainmueller and Xu, 2013), with all default options, unless otherwise noted in the text. Nevertheless, the sample size restricted the balancing to a limited number of covariates.

After the entropy balancing weights were fitted and the covariate distributions were adjusted, I proceeded to the difference-in-differences analysis. This is an effective procedure to reduce bias since any time-invariant unobservable differences between listed and non-listed municipalities are eliminated by controlling the outcomes differences in pre and post-policy moments. After this stepwise approach was completed I was able to assess possible significant effects of law enforcement on land use and land cover change, and socio-economic indicators.

3.2.1 The priority municipalities list

Late in 2007, the preliminary results of deforestation monitoring showed a rebound, in contrast to the consistent trend of reduction seen since the beginning of PPCDAm in 2004. These results led the Brazilian government to adopt new measures against deforestation. Therefore, a Federal Decree 6,321/2007 was enacted establishing that the Ministry of the Environment (MMA) should publish an annual list of priority municipalities in the Legal Amazon with recent high levels of deforestation, based on INPE's official deforestation monitoring system. So, the priority list would include the municipalities that have experienced the highest rates deforestation in recent years (Brazil, 2007; Moutinho et al., 2016). Also, these municipalities became the focus of integrated measures to strengthen control actions such as ground operations for combating deforestation, restrict new authorizations for forest clearing, and improve territorial planning and sustainable economic activities.

Consequently, the first list was released in early 2008 with 36 municipalities that had recently been deforested the most, according to the following criteria: (i) total deforested area; (ii) total area deforested in the last three years; and (iii) increase in deforestation rate in at least three of the last five years. At the same time, a decree outlined the criteria for leaving the list of priority municipalities: (i) 80% of its territory registered in the CAR, excluding areas of PAs and indigenous lands; (ii) maintain the annual deforestation rate below the limit established in an ordinance of the Ministry of the Environment, currently at 40km2/year; and (iii) for the most recent three years, the average must be 60% lower than the average of the previous three years. Presently, the list has 41 priority municipalities, known colloquially as "blacklist". Meanwhile, eleven municipalities that had met the criteria, left the list, and were re-named as municipalities with "deforestation under control" (Figure 3.3 and Appendix 9.3). Nevertheless, Cisneros et al. (2015) and Koch et al. (2019) unsuccessfully tried to reconstruct the first list based on the published criteria. This uncertainty on the initial priority list policy assignment rules helped define the method implemented in Chapter 5, as I could not use the regression discontinuity.

Furthermore, as in any research for public policy, the criteria for inclusion and exclusion of municipalities has been updated throughout implementation. The inclusion criteria became stricter in subsequent years, as deforestation was reducing. Thus, 52 municipalities have been included since 2008. In contrast, the control group was formed by municipalities that never reached the criteria to be included in the priority list, despite the tightening of the inclusion criteria. The Legal Act of 2008 ratified the strategy adopted by Ibama since 2005 to focus on the champions of recent deforestation.

As Figure 3.2 shows, the ratio of the number of fines per km2 start to increase faster in the priority municipalities compared to non-priority. Thus, the focus on strategic areas generated higher reductions than expected, while still impacting deforestation rates for the region as a whole (Dalla-Nora et al., 2014).

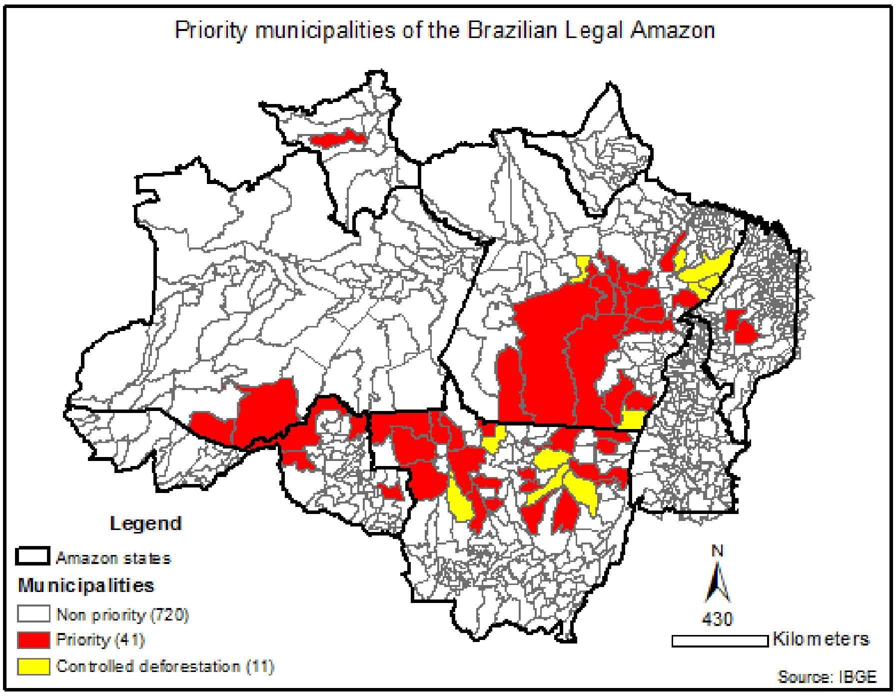

Figure 3.3 – The 772 Municipalities of the Brazilian Legal Amazon, highlighting the 52 priority municipalities. (Source: IBGE & MMA)

4 Law enforcement and deforestation

4.1 Abstract

The control of tropical forest loss presents one of the greatest environmental challenges of all time. In this context, Brazil has adopted policies during the past decade or so that have sharply reduced Amazon forest loss, a globally recognized mitigation initiative. A strong combination of different policies and actors have made this achievement possible, and environmental law enforcement is thought by some to have played a key role. Despite all these advances, it is still important and necessary to better understand where, how, and under what conditions, law enforcement has been most effective, considering an economic model of crime where the aim of law enforcement was to increase deterrence and thereby behaviour change. So, this study draws on a spatial cross-sectional methodological approach, to address whether environmental law enforcement operations on the ground, alone or in combination with other drivers, may have influenced rates of deforestation in the Brazilian Amazon for the period 2004-2014. The results confirmed the important influence of law enforcement along with other factors on reduction of forest loss. However, there are some administrative limitations to tackling law enforcement, as a shift and modernization of the environmental police strategy is imperative to face the new challenges, and the appropriate implementation of CAR policy will be crucial. This must be combined with a basket of initiatives to value the forests and support alternatives for a more balanced development, with a virtuous combination of low carbon agriculture and the maintenance of the natural assets with the appropriate compensation for that, like REDD and/or payments for ecosystem services.

4.2 Introduction

The loss of forest cover negatively impacts climate change (IPCC, 2014a) and in turn causes loss of biodiversity (SCBD, 2003; SCBD, 2014), while also increasing tropical diseases (Wilcox and Ellis, 2006), and changes in water flow regimes, both on the ground at sea and in the atmosphere (Davidson et al., 2012). Furthermore, Lovejoy and Nobre (2018) warn of 'a tipping point for the Amazon system, that will flip non-forest ecosystems'.

In this context, Brazil has adopted policies that have sharply reduced Amazon forest loss, a globally recognized mitigation initiative (Tollefson, 2012; Hansen et al., 2013; Nepstad et al., 2014; Tollefson, 2015). Consequently, these apparently successful policies have sparked interest from different areas of the scientific community who wish to understand this phenomenon from environmental, economic and social perspectives.

The vast literature on tropical forests has not yet identified any silver bullets to tackle Amazon deforestation (Rudel et al., 2009a). Instead, a strong combination of different policies and actors have made achievements to date possible (Nepstad et al., 2009; Moutinho et al., 2016; Lambin et al., 2018). Some authors have argued for fluctuations in commodity prices (Assunção et al., 2015), while others highlighted the decoupling of commodity prices in the late 2000s (Macedo et al., 2012). Soares-Filho et al. (2010) strongly argued for the importance of maintaining and creating PAs and indigenous lands, in strategic sites. Evidence also comes from increased governance and the basket of policies that were implemented including: i) the priority list (Assunção and Rocha, 2014) , ii) CAR (Alix-Garcia et al., 2017), iii) supply-chain initiatives (Nepstad et al., 2014; Lambin et al., 2018) like the soy moratorium (Gibbs et al., 2015) and cattle agreement (Alix-Garcia and Gibbs, 2017), and iv) credit restrictions on landowners involved in illegal deforestation (Nepstad et al., 2014; Assunção et al., 2016). Furthermore, other studies call attention to a change in the behavior of deforestation patterns, with an increasing predominance of small patches (MMA, 2018) and the growing participation of rural settlements (Alencar et al., 2016) and undesignated lands (Azevedo-Ramos and Moutinho, 2018).

In this context, environmental law enforcement is thought to have played a key role in reducing deforestation, as the main pillar of this sharp reduction (Assunção et al., 2013; De Souza et al., 2013; Arima et al., 2014; Nepstad et al., 2014; Soares-Filho et al., 2014; Assunção et al., 2015; Borner et al., 2015a; Borner et al., 2015b; Cisneros et al., 2015). However, all this apparent success could only be circumstantial (Schmitt and Scardua, 2015), as any new economic or political situation might bring acute instability to the system.

Ibama gained a major success with Inpe's near real time deforestation monitoring system launched in 2004 (DETER) (Kintisch, 2007; Brown and Zarin, 2013). This technology reached deforestation hotspots in their early stages, avoided extensive losses of forest, while offenders would no longer go unnoticed (Taitson, 2011; Schmitt and Scardua, 2015). So far, increasing the focus of patrol effort on priority areas has proved to be effective in reducing illegal activity in the Amazon and in influencing land use change in critical areas (Barretto et al., 2013).

Despite all these advances, it was still important and necessary to better understand where, how, and under what conditions, law enforcement was most effective (Hargrave and Kis-Katos, 2013). All studies cited so far have used deforestation data up to and including 2012. However, the characteristics of deforestation have changed since the late 2000s, ever since the percentage of deforested patches under 25ha continued to increase consistently, reaching 63% in 2010. Meanwhile large patches were severely reduced (Moutinho et al., 2016; Assunção et al., 2017; MMA, 2018). Two plausible explanations for these phenomena were discussed in Chapter 1: law enforcement focused on larger polygons first, and left the smaller ones for later; and offenders may have deliberately reduced the size of deforested areas below 25ha, to confuse the surveillance system, even in the large properties (Assunção et al., 2017).

A driving force of surveillance is dissuasion. Here, actions and tools such as fines, embargoes, and arrests by law enforcement staff help to create (i) an atmosphere of fear of being caught, for those who have committed a crime, but also (ii) those who are thinking of the risks of undertaking any illegal activities. So, the aim of law enforcement is to induce behaviour change (Schmitt and Scardua, 2015). Law enforcement has also had effects on other issues such as land use change that in turn influenced the economy of important commodities like soy and beef.

In the complex context of the Amazon: law enforcement, levels of illegality, impunity of legal processes, insecure land rights, land speculation and land abandonment, all play a part in deforestation. Thus it is appropriate to consider a model of economic crime, such as that proposed by Becker (1968), as a framework to guide the research. Here, I present a simplified version that can be summarized by the equation:

$$C = cb - (pp * cc)$$

Where

C is crime

cb is crime benefits

pp is punishment probability

cc is crime costs

The product of (pp * cc) represents the disadvantages of crime. So, as long as cb > (pp * cc), illegal activities will still continue to allow crime to pay for itself.

Besides the economic model of crime, Sutinen (1987) also proposed a quantitative model to measure the deterrence value of environmental law enforcement. The model seeks to express, in monetary terms, the risks of crime compared to profits to be obtained from illegal activities. So, it considers all stages of enforcement at which to calculate deterrence value: probability of crime detection, fine, persecution and conviction, fine value, interest rate and elapsed time for the fulfilment of the sanction. In the final analysis, as long as the deterrence value is lower than the profit obtained from crime, offenders will continue with their crimes, as found with rhinos and elephants in Zambia (Leader-Williams et al., 1990; Milner-Gulland and Leader-Williams, 1992). Deterrence has the objective of ending, or at least, reducing crime through the fear of being punished under the law. It is expected to have direct effects on the individual to not be recidivist, and indirect, on other individuals who are considering to commit a crime. So, the aim of law enforcement is to increase deterrence and thereby encourage behaviour change (Schmitt and Scardua, 2015).

In a nutshell, patterns of deforestation involve a complex chain of interactive factors that are very difficult to quantify and interpret (Araujo et al., 2009; Nepstad et al., 2009; Nepstad et al., 2014; Azevedo et al., 2015; Fearnside and Figueiredo, 2015; Moutinho et al., 2016). The aim of this chapter is to evaluate the impact of environmental law enforcement police in halting deforestation among other factors that might have influenced deforestation whether alone or in combination, and whether positively or negatively.

Therefore, it is important to extend the analysis across two dimensions, over both temporal and spatial scales, in order to provide information for new strategies and more tailored policies to improve governance. Thus, this chapter will undertake an analysis of the relationships between command and control, and deforestation, by asking the question: How and to what extent has environmental law enforcement influenced rates of deforestation in the Brazilian Amazon at the municipality level?

4.3 Methods

4.3.1 Study area

The study area for this chapter consists of 760 municipalities monitored by PRODES/Inpe during the study period, 2004-2014. Twelve municipalities were not considered by PRODES for this study. First, Mojuí dos Campos, in Pará state, was officially emancipated from Santarém municipality in 2013, almost at the end of the study. Second, the other 11 municipalities: Buriti Bravo, Cachoeira Grande, Codó, Icatu, Morros, Paraibano, Presidente Vargas, São João Do Soter, Senador Alexandre Costa, Timbiras, Vargem Grande, are all in Maranhão state, at the eastern boundary of the Legal Amazon limits defined by the meridian 44° W (Figure 4.1).

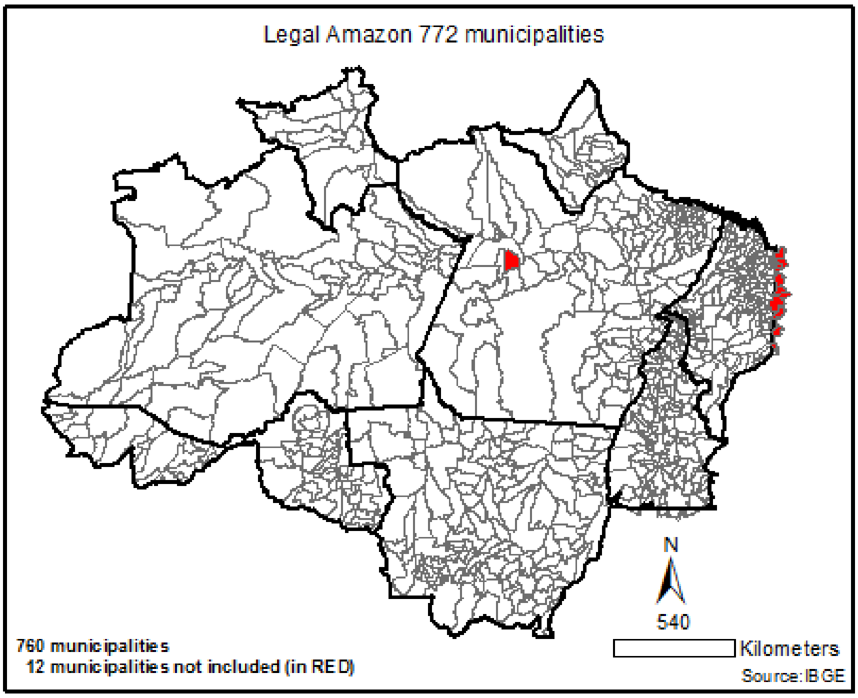

Figure 4.1 – Legal Amazon 772 municipalities, highlighting (in red) 12 not considered by Prodes/Inpe, the deforestation monitoring program of the Brazilian Institute for Space Research (11 in Maranhão state: Buriti Bravo, Cachoeira Grande, Codó, Icatu, Morros, Paraibano, Presidente Vargas, São João Do Soter, Senador Alexandre Costa, Timbiras, Vargem Grande and one in Pará state: Mojui dos Campos).(Source: IBGE)

4.3.2 Data

The datasets used for the analysis in this chapter derive from the period 2004-2014 and comprise the freely accessible data sources of the Brazilian Government (Appendix 9.1). The critical datasets chosen to investigate the influence of environmental law enforcement on deforestation were as follows:

- the fines and embargoes from the Brazilian Environmental agency (Ibama);
- annual deforestation rates, land cover and land use change, fires hotspots; climatic data including rainfall and temperature (Inpe);
- agriculture and livestock loans (Brazilian Central Bank);
- CAR – rural environmental property registry (Brazilian Forest Service);
- priority municipalities and protected areas (MMA);
- indigenous lands (FUNAI);
- settlements (INCRA);
- heads of cattle, soybean, logging, technical assistance, GDP, companies, population, Gini index, land value, roads and municipality area (IBGE).

4.3.3 Research design and methodology

As outlined in more detail in Chapter 3, this investigation focussed on the influence of law enforcement on deforestation, and followed the sequence: data collection and preparation; selection of variables; analysis; and tests of the hypotheses.

A selected group of explanatory variables was chosen based on findings of previous studies for their possible relation or influence (+/-) on deforestation in the Brazilian Amazon, and checked to avoid any severe multicollinearity (VIF) (Table 4.1).

Table 4.1 – Statistics summary of the selected variables for the models (mean and SD.), the possible impact trend on reducing deforestation (+ and/or -), and the Variance Inflation Factor (VIF) test result for severe multicollinearity.

Variable description	Abbreviations***	Obs	Mean	Std. Dev.	Possible impact on reducing def.	VIF*
Deforestation change (2004-2014) (km2)		760	-29.0	75.5		
Number of Fines (2004-2014)	ai_n_04_14	760	96.8	225.7	+	1.4
Priority municipalities	mun_prioritario	760	0.1	0.3	+	1.1
Nonforest areas (km2)	non_forest-share	760	0.3	0.4	+/-	2.0
Agriculture public loans 2004-2014 (R$)**	credagr_value_04_14	760	118.3	406.7	+/-	1.9
Livestock public loans 2004-2014 (R$)**	credpec_value_04_14	760	93.8	130.5	+/-	1.5
In-migrants population (2010)	popnaonat2010	760	43.1	22.1	-	1.4
Roads junctions (n)	roads_junctions_ibge	760	42.0	54.9	-	1.5
GDP per capita	pib_percapita_2010	760	25.0	84.5	+/-	1.6
CAR (km2)	car	760	2,666.4	4029.8	+	4.0
Settlements (2014) (km2)	settlements_14	760	472.7	1151.1	+/-	1.4
Strict Preservation protected areas (km2)	ucpi_14	760	592.6	2,842.2	+	1.5
Sustainable use Protected areas (km2)	ucus_14	760	706.1	3,059.0	+	1.6
Indigenous Lands (km2)	ti14	760	1,439.2	6,210.5	+	2.8
Annual Rainfall (mm/year)	rainfall	760	1,902.4	405.4	+/-	1.6
Maximum temp (oC)	tmax_tmq	760	26.6	1.0	+/-	3.9

* Significant values > 5.00 (analysis performed in Stata 15)
** Values deflated to Jun/2016 in Brazilian Reais (R$) using the General Prices Index (IGP-M, brazilian acronym)
*** Abreviations used in Table 4.2

On this basis, the model had 'Deforestation change from 2004-2014' as the dependent variable. Meanwhile, fines were the independent variable of interest. Furthermore, the explanatory variables to control for other factors were as follows: priority municipalities (dummy variable), the non-forest area, agriculture and livestock public loans, in-migrants population, accessibility measured by all roads/highways whether paved or not, GDP, CAR share area in the municipality, settlements, PAs for strict preservation and sustainable use, indigenous lands, annual rainfall and maximum temperature of the three hottest months of the year (June-July-Aug) (Table 4.1 and Appendix 9.4 - Figure *S* 4.1),

With the independent variables of interest: fines against embargoes presented a high correlation of 0.87, so I opted to use environmental law enforcement fines, for three reasons. First, all embargoes were associated with a fine as part of the sanctions imposed on the offender. Second, fines cover the full 10 years of the study, while embargoes only started in 2005 and so were not included in the first year of the study. Thus, fines provided the model with a more robust and consistent dataset, in this case with 70,399 against 19,348 records of embargoes. Third, in this specific situation where there are high levels of illegality, fines can represent a good measure of the presence of the environmental law enforcement staff in the field, to deter new attempts against the forest.

Next, the study undertook the cross-sectional analysis, in a standard specific to general approach (Elhorst, 2010; Golgher and Voss, 2016). The non-spatial Standard Linear Regression Model (SLM) estimated by ordinary least square (OLS) (Appendix 9.4 - Table S 4.2) was rejected by Moran and Breusch-Pagan tests. As expected, municipalities are explicitly spatial-dependent, meaning the sample is not randomly distributed but rather geographically determined. Consequently, as outlined in more detail in Chapter 3, the spatial weight matrix (Wdef) was generated for the estimated spatial models. Thus, the next section: Results and Discussion, will explore the results of the spatial models.

4.4 Results and Discussion

4.4.1 The spatial regression model analysis

The results of the SAC model definitely support the importance of the environmental police in curbing Amazon forest loss. The model results are robust and consistent, considering the wide variety of perturbations to which the models have been exposed. The test of the null hypotheses to impose restrictions to the more general model (SAC) and adopt the SAR ($\rho = 0$) or SEM ($\lambda = 0$) were not confirmed, as both were rejected (Appendix 9.4 – Table *S* 4.3). Accordingly, the following paragraphs will present and discuss the results of the impact evaluation on deforestation SAC model (Table 4.2).

The overall results of the SAC predicted most of the variables as expected. Therefore, the next paragraphs will explore how policies implemented by the Brazilian government, as part of their action plan to prevent and control deforestation, have contributed to reduce deforestation. By contrast, the results also suggest that some policies, including settlements and GDP, an economic indicator, have more influence on forest loss than others.

Fines

The model suggests a significant marginal effect of fines on deforestation, including indirect effects, spillover to other municipalities. Indeed, for each fine there is a reduction in deforestation of 9.75 ha (4.89-14.62) ($p<0.001$), based on the 95% confidence interval (Table 4.2).These results provide good evidence of the role of law enforcement in halting deforestation, as found in previous studies (Assunção et al., 2013; Hargrave and Kis-Katos, 2013; Assunção et al., 2015; Borner et al., 2015a). Fines and embargoes are a consequence of the presence of law enforcement officers on the ground in the Amazon. Moreover, the presence of environmental police increases the likelihood of detection and capture.

Indeed, since 2004, the first year of PPCDAm, Ibama's ground operations in priority areas have become more frequent and prolonged. A clear change in the law enforcement strategy was catalysed by a considerable increase in the availability of financial and human resources. Furthermore INPE successfully developed and operated the near real time forest loss detection system. Since 2004, DETER has guided the law enforcement teams on the ground. In the early days of the system, it started providing 250m spatial resolution MODIS data once a month. It has since evolved to the current version, DETER-B, with daily information at 64 and 56m spatial resolution from WFI sensor on board of CBERS-4 and AWiFS from the Indian Remote Sensing Satellite (IRS), respectively (INPE, 2016a).

Table 4.2 – Impact evaluation of deforestation SAC model: direct, indirect and total effects.

Average impacts (n=760)	dy/dx	Delta-Method Std. Err.	z	P>z
direct				
Number of Fines (2004-2014)	-0.098	0.025	-3.93	0.000
Priority Municipalities	-63.881	16.536	-3.86	0.000
Non-forest area share	26.794	6.475	4.14	0.000
Agriculture loans value 2004-2014	0.004	0.007	0.57	0.572
Livestock loans value 2004-2014	0.012	0.026	0.44	0.657
In-migrants in 2010	-0.324	0.099	-3.27	0.001
Roads/Highways junctions (km)	-0.206	0.082	-2.50	0.012
GDP per capita	0.048	0.022	2.15	0.031
CAR	-0.007	0.002	-3.12	0.002
Settlements area 2014	0.006	0.002	2.94	0.003
Strict Preservation PA 2014	-0.002	0.001	-2.08	0.038
Sustainable Use PA 2014	0.006	0.002	2.54	0.011
Indigenous Lands 2014	-0.001	0.001	-1.19	0.234
Rainfall (mm/year)	0.002	0.008	0.23	0.820
Average Temp hottest Quarter (Jun-Aug) (oC)	-2.132	3.466	-0.61	0.539
indirect				
Number of Fines (2004-2014)	0.241	0.122	1.98	0.048
Priority Municipalities	158.051	61.169	2.58	0.010
Non-forest area share	-66.292	35.505	-1.87	0.062
Agriculture loans value 2004-2014	-0.010	0.020	-0.52	0.603
Livestock loans value 2004-2014	-0.029	0.067	-0.43	0.669
In-migrants in 2010	0.801	0.459	1.74	0.081
Roads/Highways junctions (km)	0.510	0.336	1.52	0.129
GDP per capita	-0.120	0.078	-1.54	0.124
CAR	0.016	0.011	1.50	0.134
Settlements area 2014	-0.014	0.008	-1.80	0.072
Strict Preservation PA 2014	0.006	0.004	1.50	0.133
Sustainable Use PA 2014	-0.014	0.011	-1.37	0.172
Indigenous Lands 2014	0.003	0.003	0.91	0.363
Rainfall (mm/year)	-0.004	0.019	-0.23	0.817
Average Temp hottest Quarter (Jun-Aug) (oC)	5.274	7.926	0.67	0.506
total				
Number of Fines (2004-2014)	0.144	0.115	1.25	0.210
Priority Municipalities	94.170	63.696	1.48	0.139
Non-forest area share	-39.498	32.890	-1.20	0.230
Agriculture loans value 2004-2014	-0.006	0.013	-0.48	0.631
Livestock loans value 2004-2014	-0.017	0.042	-0.41	0.683
In-migrants in 2010	0.477	0.410	1.16	0.245
Roads/Highways junctions (km)	0.304	0.283	1.07	0.284
GDP per capita	-0.071	0.065	-1.11	0.268
CAR	0.010	0.009	1.04	0.300
Settlements area 2014	-0.009	0.007	-1.20	0.229
Strict Preservation PA 2014	0.003	0.003	1.09	0.275
Sustainable Use PA 2014	-0.009	0.009	-0.98	0.328
Indigenous Lands 2014	0.002	0.002	0.75	0.456
Rainfall (mm/year)	-0.003	0.011	-0.23	0.817
Average Temp hottest Quarter (Jun-Aug) (oC)	3.142	4.712	0.67	0.505

The combination of the daily satellite monitoring system with the new law enforcement strategy has significantly changed the course of deforestation in the Brazilian Amazon during the past 13 years. Brazil has become internationally recognized for its strong approach towards climate change mitigation and its implementation, a successful policy to reduce tropical deforestation with a major input from law enforcement (Assunção et al., 2015; Tollefson, 2015).

New Policies: Priority Municipalities and Rural Environmental Registry (CAR)

Secondly, priority listed municipalities reduced deforestation more effectively 6,388 ha (3,147-9,629 ha (p<0.001) than unlisted municipalities. At another scale, for every addition km2 of CAR, 0.6 (0.2 to 1.0) ha (p=0.002) of forest loss was deterred (Table 4.2).

In first place, the priority municipality list, also known as the 'black list[30]' (Assunção and Rocha, 2014; Moutinho et al., 2016), can be considered an operational and short term strategy. The list officially marked the priority areas in which command and control had been operating since 2005, with immediate effect and intensification of ground operations, and generate indirect effects in surrounding areas (Table 4.2 and Figure 3.2).

Furthermore, the priority list turned out to be a cost-effective means to stimulate co-responsibility of district-level political elites. In other words, deforestation was ultimately also a problem of mayors and the local society (Cisneros et al., 2015). No mayor wanted to be listed for reputational and economic reasons. Also, investors did not want their businesses to be associated with areas supporting high rates deforestation. This is not good for their institutional image, so potential investors would move and/or invest somewhere else, often to unlisted neighbouring municipalities.

Thus, listing provided the opportunity to mobilize the municipality governments, their productive sectors and civil society in search of partnerships with non-governmental organizations, state and federal government, and even international support to take the necessary measures and get off the "blacklist". For instance, Alta Floresta municipality, in the north-west region of Mato Grosso state, was listed in 2008, and its high levels of deforestation led to a shortage of potable water for the population. This was reversed by mobilizing the local government, producers and civil society with the support of the Amazon Fund. These were discussed further by local NGOs and EMBRAPA, to restore springs and riparian forests, and to implement pilot projects to intensify the use of pasture,

[30] NGOs, researchers and the press referred to the municipalities' priority list as the "black list" of the top deforesters' municipalities in the Brazilian Amazon.

to increase occupation and productivity without having to clear new areas. Four years later, in 2012, after intensive mobilization, Alta Floresta left the list of priority municipalities.

Synchronously, the Monetary Council of the Central Bank of Brazil released Resolution 3545 (BACEN, 2008), to strengthen the line of action of Decree 6,321/07, by setting new environmental standards in order to gain access to rural credit in the Amazon municipalities, especially for those denoted PM by restricting access to rural credit. Therefore, credit was conditional upon the presentation of documents proving the possession of the land and the environmental compliance, including proof of the absence of embargoes and/or areas deforested illegally on the property. In another important front against deforestation, Assunção *et al.* (2016) suggest that credit restrictions helped contain deforestation, mostly by reducing cattle loans, the main driver of deforestation.

So far, the priority list established in 2008, had already shown a clear impact on reducing deforestation and an unexpected but very important positive result with natural regeneration (see Chapter 6).

In turn, CAR policy suggests a mid to long term response. As a more recent policy (Brazil, 2012a; Brazil, 2012b), CAR still showed modest results in view of its future potential to containing illegal deforestation, by significantly increasing compliance with the Forest Code and consequently for the recovering of degraded areas. These results support those of Alix-Garcia et al. (2017) and Azevedo et al. (2017) who also do not indicate any important reductions in deforestation after CAR policy implementation. Moreover, CAR is being progressively incorporated as a mandatory requirement for farmers in obtaining bank loans for agriculture and livestock.

Therefore, CAR is expected to play an important role in reducing deforestation in the near future, since private properties contributed annually with the largest portion of forest loss in the Amazon. CAR used to embrace almost half of annual deforestation in 2004, but dropped to 27% in 2009. However, since then it has shown a consistent upward trend and reached 34.8% in 2014 (Appendix 9.2 – Table *S* 2.1).

Moreover, deforested areas in private properties, whether or not with CAR, were further categorized into three groups: legal, illegal and unintentional illegal. The first group represents landowners with the appropriate authorization to suppress native vegetation, in compliance with the environmental law. The second group is represented by the different kinds of offenders, always operating outside and in disagreement with the current environmental law. The last category represents landowners willing to work in compliance with the law and only use the amount of land that is permitted.

However, due to delays in obtaining the proper authorization from the competent authority, usually the state environmental agency, they are “forced” to clear the area and become illegal deforesters**.**

In addition to the CAR policy implementation, there is a clear role for state environmental agencies to become more efficient in controlling forest activities and provide transparency regarding ‘information on licensing and permits for removal of vegetation in the Amazon’ (Hummel, 2016 p3). For instance, a recent ordinance of the Ministry of the Environment (2018) requires states to share and include all authorized vegetation removal in the federal system (SINAFLOR). It aims to fill a huge gap among the federal and state governments, regarding the legality of deforested areas (Hummel, 2016). Certainly, it will help the federal law enforcement to be more efficient and focused on illegally cleared areas.

For instance, during operations on the ground, it is often difficult to identify the offender, even when people have been caught, because they are working, often without any identification, for someone whom they do not know by their full name, only by a nickname.

Thus, a simple cross-check of state authorizations and CAR could allow the authorities to separate legal from illegally deforested areas, saving time and scarce financial resources for operations in the field. This would probably scale up the number of fines in the short-term due to the level of illegality that persist, by simply sending the fine by mail or e-mail, as recently implemented by Ibama (2017). Consequently, field enforcement operations can focus on illegal deforested areas outside of the CAR system. Accordingly, it was predicted that there would be greater compliance in the mid to long term with the legislation. By contrast, there would be less illegality, due to the level at which control was imposed. Thus, the consequences of breaking the rules is to be part of a public list of non-compliant properties, constantly checked by traders, industries and other commodity buyers, in order to avoid purchase from properties in disagreement with environmental legislation.

Protected Areas and Indigenous Lands

Another outcome predicted by the spatial model is that for every additional 100 km2 of strict PAs there would be a reduction in deforested area of 0.23km2 ($p=0.038$). By contrast, sustainable use PAs show an increase in deforestation of 0.58 km2 ($p=0.011$) for the same 100 km2. Surprisingly, Indigenous Lands showed no significant effect. Taken together, this represents a mix of expected and unexpected results.

Figure 2.7 confirms the expected result that strict PAs are the lowest contributor to forest loss with only 0.4% share in 2014 (details Appendix 9.2 – Table *S* 2.1). It was predicted that a similar result would hold for sustainable use PAs as a barrier to halt deforestation. Instead, the spatial model suggests the opposite, with this PA category contributing with more deforestation. Sustainable use PAs responded for 9% of 2014 annual deforestation against 6% in 2011, an undesirable and worrying growth.

In reality, the latter category presumes the sustainable use of a portion of the PA, but in some cases, traditional communities are clearing areas for non-traditional activities, like cattle and agriculture, and not only for subsistence. For instance, as reported elsewhere, cattle became a safe way of saving money for family and personal emergencies, whether or not health-related (VanWey et al., 2012).

Besides, MMA (2018) reports that for the period 2012-2015, approximately 50% of annual forest loss is highly concentrated in only 20 sustainable use PAs. So far, the sustainable use PAs that lead the rankings of deforestation comprise the formal Brazilian categories of: Forests (National and State) and Extractive Reserves (Resex), most of which span the deforestation frontier.

A further notable result from MMA (2018) is that state preservation areas, especially those for sustainable use, are more deforested than federal protected areas. It is important to note here, as in the MMA 2018 report, that the category, Environmental Protection Area (APA, Brazilian acronym) was not considered in the analysis because it supports public and private lands, responding to the same logic of land use of private areas.

Likewise, during the study period of 2004-2014, around 540,000 km2 of PAs were created in the Brazilian Amazon, adding 82%, and reaching a total of 1.2M km2, nearly 24% of the area of the Legal Amazon (Table 4.3 and Figure 4.2). According to SCBD (2010a) this represents close to 75% of all terrestrial PAs created globally in the early 2000’s.

Moreover, the more recently established PAs were created closer to deforestation frontiers with intense land use conflicts (Figure 4.2) so they could act as natural barriers to contain the advancement of forest clearing (Soares-Filho et al., 2010). Thus, these PAs become more susceptible to illegal deforestation, as described in Section 2.1, and reported elsewhere (MMA, 2018).

Table 4.3 – Brazilian Amazon Protected Areas before and after PPCDAm (in km2). (Source: MMA)

Year of PA creation	Strict Preservation	Sustainable Use	Total
Before 2004	251,232	398,277	649,509
2004-2014	200,141	337,994	538,135
Total	451,373	736,270	1,187,644

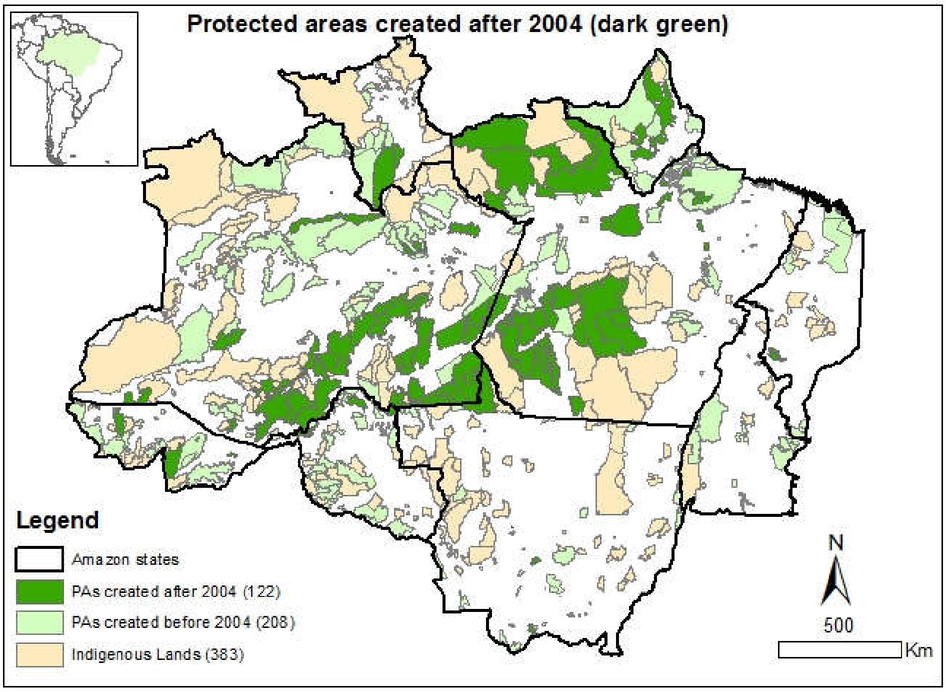

Figure 4.2 – Brazilian Amazon Protected Areas and Indigenous Lands, highlighting 122 PAs (dark green) created after 2004, the initial year of PPCDAm.(Sources: MMA, FUNAI, IBGE)

Counterintuitively, indigenous land had no significant effect in reducing deforestation during the study period (2004-2014). Indigenous land occupies 23% of the Brazilian Amazon. Historically, indigenous people have made very minor contributions to the overall levels of deforestation. Furthermore, they showed a very clear downward trend from 5.1% in 2009 to 1.9% in 2014, respectively (Appendix 9.2 – Table *S* 2.1). So, the low levels of deforestation in indigenous lands would not have been expected to have a pronounced impact on the overall reduction in deforestation. Indigenous land has played an important role as a green barrier against the expansion of the agricultural frontier (Soares-Filho et al., 2010).

Nevertheless, Indigenous land suffers from constant intrusions of illegal loggers aiming to take valuable timber, as well as illegal mining, predominantly of gold. Other invasions include those by ranchers for soy and cattle, in some cases with the consent of indigenous peoples. More recently, indigenous groups have ventured to produce soy in partnership with soy producers as a way of further improving their quality of life (Cirne and Rodrigues, 2018). In turn, this can become the biggest threat to the integrity of the forests in their natural habitats, with important legal implications, and consequences for deforestation, climate change and biodiversity loss.

Rural Settlements

The model results also suggest that, for every 1km2 of rural land reform settlement there is an indicative increase of 0.5 (0.2-1.0) ha of deforestation. This trend can be confirmed with the increasing contribution of settlements to the total annual deforestation, which rose from 19% in 2004 to 34% in 2011 (Appendix 9.2 – Table *S* 2.1). Deforestation then stabilised at around 31% in the following three years (Perz et al., 2010; Alencar et al., 2016; Assunção and Rocha, 2016; MMA, 2016). So far, land reform settlements are consolidated as the second major category to contribute to deforestation, surpassing even private lands from 2009-2011, as leader in the deforestation category (Figure 2.7).

It is important to highlight some aspects of the complexity of settlements in the Amazon. First, Brazil has a long experience of waves of occupation in the Amazon, outlined in more detail in Chapter 1 (Section 1.2). More recently, in the early 1960s, landless peasants from other regions were encouraged/stimulated to move to the Amazon. Brazil promoted state-sponsored land reform settlements programmes (Brazil, 1964; Araujo et al., 2009; Le Tourneau and Bursztyn, 2010).

Overall, the land reform programme has settled over 1.3M families in 9,389 land reform settlements, covering 88M ha (INCRA, 2018), and with more than 85% of settlements concentrated within the limits of the Brazilian Legal Amazon. Indeed, the last 15 years was characterized by a marked increase in the number of land reform settlements as part of the Brazilian land reform policy. In 2014, settlements covered an area of 376,000 km2, a substantial increase of 71% since 2002 (Assunção and Rocha, 2016). In the early 2000s, settlements were established in remote areas (Assunção and Rocha, 2016) with higher forest cover than in the late 1990s (Alencar et al., 2016). In turn, this inevitably led to deforestation on the arrival of settlers, at least for their subsistence agriculture, to fulfil settlements' objectives. This was usually based on slash-and-burn technologies and shifting cultivation with a range of fallow cycles (Fujisaka et al., 1996; Futemma and Brondízio, 2003). In addition, results from Farias et al. (2018) point out that more densely occupied rural settlements experience more deforestation.

Historically, rural settlements receive insufficient technical assistance, are associated with poorly capitalized settlers, always dependent on credit opportunities, and low productivity after 3-5 years (Brondizio, 2006; Alencar et al., 2016). In turn, this led to early abandonment and the need for new areas to produce, usually forested areas within their own Legal Reserve, comprising 80% of the property in the Amazon. In addition, smallholders face difficulties to compete in the market with large producers of commodities (Assunção and Rocha, 2016). As will be explored in Chapter 6, this has a positive impact on natural regeneration, but with the undesirable cost of possible new deforested areas and increased migration to urban areas (Futemma and Brondízio, 2003; D'Antona et al., 2011).

Another reason for settlements to show an increasing trend in deforestation may be related to illicit associations with illegal loggers and commodity producers. The former represents a way for settlers to make some money by allowing loggers to take valuable timber from their Legal Reserves and sometimes in exchange for clearing the land. In turn, the latter represents land re-concentration (Alencar et al., 2016), of decapitalized settlers in search of a more stable income, in some cases to sign agreements' for land rent to annual crop producers or livestock. In other cases, they sell or are coerced into selling the land unofficially to people who are operating illegally in the region, forcing beneficiaries of the land reform to move.

So far, settlements are a growing contributor to deforestation and need more attention from the government (Caladino et al., 2012; Alencar et al., 2016; Moutinho et al., 2016; Farias et al., 2018). In 2012, the Brazilian agrarian reform and land tenure regularization agency (INCRA) created a Programme called "Green Settlements" (INCRA, 2012), following the principles of PPCDAm. They were willing to change the course of land use and deforestation in land reform settlements, and become environmentally sustainable and economically autonomous (INCRA, 2012). So, its impact will have to be assessed in the near future to check its effectiveness in curbing deforestation and promoting sustainable development for its beneficiary smallholders.

In-migrants

Then, the models showed that a 1% annual increase of in-migrants living within a municipality population contributed to reducing deforestation from 13ha to 52ha ($p<0.001$). Such a response was not expected considering the long history of waves of occupation in the Amazon that accompany deforestation (Moran, 1981; Perz and Skole, 2003b; Brondizio and Moran, 2008; Brondizio and Moran, 2012; VanWey et al., 2012). Migrants move to new regions for mainly two reasons. First, they may be a beneficiary of the government land reform programme known as 'settlements', or in search for the opportunity of a better life and cheap land. Thus, independently of the motivation, on arrival, outsiders will at least start with subsistence agriculture. Therefore, in the short term, deforestation can be expected to increase. But, in the mid to long term, it could be diminished once farmers are already settled and producing in compliance with the current environmental legislation. A closer look may identify some insights for such results emerging from this analysis.

Mato Grosso supports those municipalities with the highest percentages of in-migrants (Appendix 9.4 – Figure *S* 4.1(G)), as the municipalities with the highest GDP per capita in the Amazon (Appendix 9.4 – Figure *S* 4.1 (I)), and supports a vast network of roads (Appendix 9.4 – Figure *S* 4.1 (H)). This combination of factors may have positively influenced the rates of deforestation, once annual crops had become well established (Appendix 9.6 - Figure *S* 6.1 (D)), more intensive and with capitalized labour (Angelsen and DeFries, 2010; Macedo et al., 2012; Picoli et al., 2018), as dependent on a good network of roads to take the commodities to national and international markets.

Also, Mato Grosso is the largest producer of annual crops in the region, especially of soy, due to the predominance of farmers with origins in the south region of Brazil, a region with long tradition of soy production. Furthermore, Terraclass reveals that, in a 10-year period from 2004-2014, 16,504 km2 (36%) of annual crops in 2004 still remain as cropland in 2014, 40% (17,794 km2) comes from pasture and 17% (7,665 km2) are newly deforested areas, the latter represents only 5% of all forest losses in that period (Table 2.10).

Add to that, a strong and constant development of science and technology from the Brazilian Agricultural Research Corporation (EMBRAPA). For instance, the last 40 years have witnessed a yield increase in soy of 64%, reaching 2,870 kg/ha in 2015 (CONAB, 2017). In turn, the same report also reveals a substantial increase of 378% of the soy area planted. In the case of Mato Grosso, it is evident in its central area of the state, mostly displacing pastures. But nevertheless, still suggesting there was indirect deforestation (Figure 2.8).

Later, however, the same report CONAB (2017) disclosed a slowdown of yield gains to 20% in the last 20 years, compared to 67% gains in the previous 25 years (1976-2000), through hitting a yield threshold. So, its yield expansion in Brazil will inevitably come from area expansion, raising a red flag for deforestation. Unless that is, scientists and a new wave of technological improvements can manage to take experience from research to farmers' fields, where there already exists more productive soy varieties that can raise the yield to another level. Nevertheless, scientists are still struggling with the high inputs and production costs.

Even so, it could still be a positive outcome for combating deforestation, if expansions carry on being dominated by pastures displacement, and they occur in areas highly suitable for agriculture. Sparovek et al. (2012) drew note that a modest increase of pasture occupation from 1.1 to 1.5 head/ha and off-take of 30%, would release around 69M ha of pastures for other uses. However, if pasture occupation is not well guided, it could go in the opposite direction, expanding over forests, due to the higher costs of recovering degraded lands and pastures, compared to open forested areas.

Land scarcity and higher land values may change the course of such behavior, in some regions where area expansion is no longer an option, invest in yield gains will turn to be the only viable option (Soler et al., 2009).

The soy moratorium has also played a key role in reducing new deforestation for annual crops after 2008 (Gibbs et al., 2015), at the same time as law enforcement presence created pressure and imposed constrains. The Soy moratorium report (Abiove, 2017) shows that only 1.2% of soy cultivation in the Amazon (2009-2017) did not respect the agreement. However, in their sampled properties in Mato Grosso, Azevedo et al. (2015) found that 65% out of the 82% compliant with the soy moratorium, are not in compliance with the Forest Code legal reserve requirements.

Roads and highways

Counterintuitively, the results suggest that a better network of roads and highways could reduce deforestation in 21 ha (4.5 to 37ha). However, roads in tropical forests are another controversial topic, as reported elsewhere (Angelsen and Kaimowitz, 1999; Laurance et al., 2002; Chomitz and Thomas, 2003; Fearnside and de Alencastro Graça, 2006; Kirby et al., 2006; Perz et al., 2007; Pfaff et al., 2007; Arima et al., 2008; Weinhold and Reis, 2008; Perz et al., 2012; Perz, 2014; Laurance et al., 2017). This is a central point of an economic gains trade-off, in which well-maintained roads can lower input costs and raise output prices and profits.

Roads make distant areas accessible, feasible and profitable in the Amazon. Thus, roads stimulate deforestation for agricultural activities along its verges (Soares-Filho et al., 2005; Aguiar et al., 2007; Pfaff et al., 2007; Soler et al., 2009; Walker et al., 2013; Laurance et al., 2017; Pfaff et al., 2018). Furthermore, roads will undoubtedly reduce transport costs for farmers' products (Hargrave and Kis-Katos, 2013). However, this will only occur if roads are well maintained, a hard task considering the high levels of rainfall in the Amazon and the limitations placed on government capacity to maintain those roads/highways.

Gross Domestic Product (GDP)

As expected, an increase of one unit in GDP per capita comes with an increase of 4.8 ha (0.4 to 9.3 ha) on deforestation. As seen in Figure *S* 4.1 (I) (Appendix 9.4), the most capitalized municipalities are concentrated in Mato Grosso state, where annual crops are dominant and persistent, especially in the central area with most valued lands, and investments go to higher value commodities, intensive labour and well served by roads, a typical agglomeration pathway of intensification. As a consequence, this area in Mato Grosso experiences less intensive land use change of croplands. Only

10% (1,585 km2) was turned into pasture, and less than 1% (150 km2) into natural regeneration (Table 2.10).

Additional controlled variables

Finally, the model has generated some controlled variables with no significant responses. It was predicted that subsidized loans for agriculture and livestock would have an impact on deforestation. Counterintuitively, however, the results of the model reveal no significant effects. As for annual rainfall and temperature with no significant effect on curb deforestation.

“Environmental crime in the Amazon region is not for amateurs”, Ibama’s director of Environmental Protection once stated (*personal communication*). Criminal organizations are highly sophisticated and well equipped to monitor the government actions, as illustrated by the following anecdotes.

After a long period of investigation in 2015, Ibama and the Federal Police, discovered and dismantled a well-equipped Remote Sensing Lab in Sao Paulo, working and providing strategic information for illegal deforesters operating in the Amazon region, based on the open access government information system. This was a clear attempt to anticipate the next moves of the government law enforcement teams and temporarily suspend activities in areas that are most susceptible to ground operations of the environment police. In another high profile example, the criminal considered the greatest deforester of the Amazon, Ezequiel Castanha (JN, 2015), was arrested while operating in Novo Progresso region in the south-west of Pará state. After his arrest, deforestation dropped by 65% in the region in which he was operating.

Moreover, crime organizations focus heavily on land grabbing in order to establish their operations, sometimes removing anyone who opposes this approach. Global Witness wrote a report on crimes associated with land rights across the globe, and Brazil was the worst offender in 2017, with 57 out of 207 killings globally (Witness, 2018). A chronic problem in the Amazon can be exemplified by the deaths of two emblematic personalities along the recent disputes for land in the region. First, in 1988, Chico Mendes, a rubber tapper, was murdered in his house in Acre state by farmers (Globo, 1988). More recently, in 2005, already in the context of PPCDAm, Dorothy Stang, an American sister, fighting for the poor (smallholders) and the environment, was killed in an ambush in Anapu in the state of Pará (BBC, 2013).

4.4.2 Study limitations

This chapter did not intend to explore all aspects of deforestation dynamics in the Amazon in depth. Instead this chapter had the objective of high-lighting the explanatory factors and drivers that might have been considered important for law enforcement and deforestation.

First, my review of land tenure rights has only scratched the tip of the iceberg. Land tenure continues to be a huge challenge for the Amazon region (Azevedo-Ramos and Moutinho, 2018). Inevitably, some of the expansions of pasture are based on land speculation, land grabbing and false land title documents. All this sought to maintain control over a large land area and take advantage of speculative opportunities (Garrett et al., 2017). In other words, through a profit-seeking (Bowman et al., 2012) and appropriation of future land values when infrastructure development comes to the region (Frey et al., 2018).

Second, the consolidation of the Amazon Soy Moratorium has shed light on the possible leakage of deforestation in the Cerrado, another important issue that deserves more detailed study. The soy agreement made it possible to allow very limited forest displacement in the Amazon. Only 1.2% of soy was planted in disagreement and became listed (Agrosatelite, 2016). The list encourages traders and buyers not to buy from these producers. Besides, it may have generated leakage to Cerrado, where surveillance and illegality are lower. Moreover, the legal reserve requirements in Cerrado is lower, 35% if Cerrado is within the Legal Amazon and, only 20% for the remaining Cerrado outside the Legal Amazon, putting Cerrado at risk, as it is an attractive place to expand, as has been documented in recent years (Strassburg et al., 2017). The result is that native Cerrado vegetation has been lost at a faster pace than Amazon, and almost half of the native vegetation has already gone (Figure 4.3 and Appendix 9.4 - Table *S* 4.4).

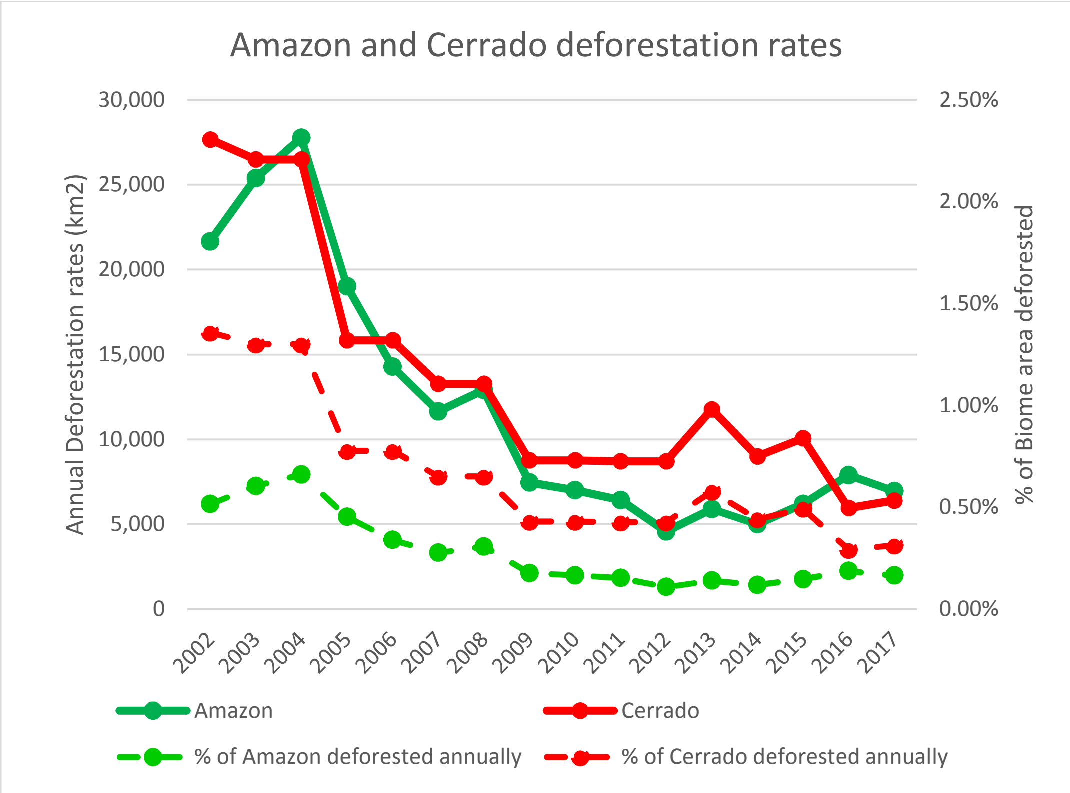

Figure 4.3 - Amazon and Cerrado annual deforestation rates (km2,) and annual percentage of native vegetation loss. (Source: INPE)

Further investigations are necessary to better understand the possible connections of these two events and indicate what could be the best approach and sequence for policy-makers to tackle them in combination.

4.5 Conclusions

Deforestation has reduced sharply in the Amazon over the past 1.5 decades. This has been due to the strong support of the environmental police. Some battles have been won. However, the war is far from over. The risks of a resumption in deforestation are still present and could be summarized as follows: 'as long as crime pays I will deforest` (Becker, 1968; Meyfroidt, 2013; Schmitt, 2015). This simple phrase reflects the economic theory of crime, when the agent foresees an economic advantage that is greater than the risks of being detected, caught and penalised.

This nexus exposes some limitations for the administrative environmental law enforcement penalties. First, not all detections within the monitoring system receive a fine. Second, when fined, it takes over 3 years for the case to be put on trial for the first time. Moreover, only one out of four fines reach this point. Third, only one in five of illegal deforestation areas are embargoed. Fourth, the fines are not paid, only 0.2%, in the Amazon context (Schmitt, 2015).

The low likelihood of punishment, after all the work done in the field, spreads the idea among offenders that they can act with impunity. At the end of the day, this will reflect on their illegal actions and they will continue to think that illegality still pays off. For this reason, the environmental police still remain a very powerful ally and are essential in any strategy to combat deforestation and protect areas of natural regeneration. However, the command and control strategy must continue to evolve in order to face the new challenges of deforestation and land use in the Amazon. It is critical that other policies advance hand-in-hand with the environmental law enforcement to avoid unnecessary land conversions (Ludewigs et al., 2009).

Thus it is imperative that the environmental police strategy undergoes modernization. Law enforcement has to reflect both on ground operations and judicial concerns, as demonstrated in Schmitt (2015) model. This involves the whole formal procedure and stages of the administrative process for an environmental violation: detection, notice (fine), trial, conviction, payment, fine value, embargo value, value of seizure, and the offense time trial. Only a good balance of action at all stages will change the course of impunity and increase the power of dissuasion and deterrence. In other words, field work must be complemented with intelligence networks, data mining, and offenders paying the fines. Furthermore, fieldwork should arrest and bid the offenders' assets including cars, trucks, bulldozers, boats, soy and cattle. The judiciary must act faster, while convicted offenders must be detected earlier, and remain longer in jail. It is clear, when a criminal leader is taken to jail, deforestation drops significantly in that region.

Moreover, a new paradigm concerns smaller deforested areas (Schielein and Börner, 2018), to challenge the capacity and creativity of the environmental police. In this sense, the full implementation of CAR will be sufficiently decisive to halt deforestation and for degraded lands to fully recover. It is a necessary change in the environmental police strategy to curb deforestation. More than ever, the strategy associated with CAR is expected to encourage farmers to be in compliance with the environmental legislation and the Forest Code. Therefore, in the mid to long term, fines are expected to reduce substantially on private lands. Consequently, Brazil can move towards its NDC goal of "Zero Illegal Deforestation by 2030" (Brazil, 2015).

This goal, however, is not achievable only through stopping illegal deforestation within private properties. Araujo et al. (2009 p.2467), in their conclusion, make the observation 'that insecure property rights in land drives deforestation in the Brazilian Amazon'. Similarly, (Azevedo-Ramos and Moutinho, 2018) argue 'that a faster and more cost-effective way of reducing deforestation in the Brazilian Amazon would be the immediate allocation of ca. 70 million hectares of still undesignated public forestlands'. Therefore, almost hand-in-hand with CAR comes the Amazon land tenure/designation and the chronic challenge of property rights. Of relevance here is that CAR is only about environmental compliance of the property and has nothing to do with land and property rights, a task for the Institute for Colonization and Land reform (INCRA), and states land institutes.

Having said that, solving the complex issue of deforestation, illegalities and crimes associated with land rights (Araujo et al., 2009) and unsupervised public lands (Azevedo-Ramos and Moutinho, 2018) could be drastically reduced.

This chapter has explored the impact of environmental law enforcement police on Amazon deforestation. The next two chapters will investigate the possible influence of environmental police on the land use attributed to deforested areas, focusing on agriculture, cattle ranching and secondary vegetation, the most representative in land use dynamics.

5 Law enforcement and land use: dynamics of land cover change

5.1 Abstract

In the last 50 years, agriculture has expanded at the cost of converting natural areas, particularly in developing tropical countries. These currently cover 49% of the planet's ice-free terrestrial surface. This expansion is driven by rising demands for food, due to global population and income growth, especially in developing countries, as meat consumption increases. This places agricultural activities, named annual crops and livestock systems, as a central driver of tropical forests loss, and a severe risk to biodiversity, including: PAs; several environmental services; increases in GHG emissions; and changes in hydrological cycles. Since 2004, Brazil has implemented conservation policies that have drastically reduced Amazon forest loss and emissions, indeed even changing the distribution of emissions of some Brazilian sectors. In 2005, 70% of Brazilian emissions originated from land use change and forests sectors, but this has significantly reduced to 27% by 2010. In contrast, the agricultural sector increased from 14 to 32% in the same period, and energy showed a similar trend from 11 to 29%. The influence of law enforcement on the reversal of Amazon deforestation is well documented. However, less attention was given to possible "side effects" of the intense command and control on reshaping land use dynamics after deforestation. In this chapter, I propose to evaluate the extent and direction of the possible influence of law enforcement on land use change for the significant land-cover types in the Brazilian Amazon, after the priority municipalities policy was enacted in 2008. These AFOLU include annual agriculture, livestock, and secondary vegetation (natural regeneration). I used a difference-in-differences with entropy balance approach at the municipality, private properties and settlement levels, to evaluate the priority municipality (PM) policy implemented in 2008 that led to an intensification of law enforcement on target municipalities. The results show an increased persistence of agriculture and clean pastures, as a substantial increase in natural regeneration (abandonment), a reduction of dirty pastures, and suggests an influence of law enforcement on this land use dynamic. Annual crops, mostly soy, turned out to be an agglomerated economy in the central area of Mato Grosso, while extensive pastures are more widespread with low levels of occupation and also as part of land speculation. Both activities have shown signs of intensification and sparing lands, at least for natural regeneration. So, conservation policies based on law enforcement contribute to reshaping AFOLU systems in the Brazilian Amazon, certainly, not alone but in combination with other policies and initiatives. It is clear from this study that law enforcement has become a stronger component on farmers' land use investments and decision-making processes. Thus, while illegality prevails, environmental and land tenure law enforcement will be mandatory to ensure the effectiveness of a sustainable

intensification, reduce forest loss, and fulfills the role of sparing lands for conservation, agriculture and ultimately achieve balanced land use systems.

5.2 Introduction

In the last 50 years, agriculture has expanded at the cost of converting natural areas, particularly in developing tropical countries, which currently cover over 49% of the planet's ice-free terrestrial surface (IPCC, 2019). This expansion is driven by rising demands for food, due to global population and income growth, especially in developing countries, as meat consumption increases (Dobermann et al., 2013).

This places agricultural activities, namely annual crops and livestock systems, as a central driver of tropical forests loss, and a severe risk to biodiversity, PAs, many environmental services, leading to increases in GHG emissions and changes in local and regional hydrological cycles (Garrett et al., 2018).

As a result, there is a clear need to shift from intensive to low energy production systems, to reduce the environmental footprint, through transformative changes in food production and consumption: increasing productivity; protecting land resources; increasing water use efficiency; pollution mitigation and increasing ecological functions in more diverse landscapes.

Since 2004, Brazil has implemented conservation policies that have drastically reduced loss of Amazon forests (Assunção et al., 2015; Tollefson, 2015), the opposite of the upward trend forecasts of tropical deforestation and land use models from the 2000s' (Dalla-Nora et al., 2014). As a result, Brazil has reduced its emissions by more than 50% (2005-2010) (Brazil, 2016) and reversed deforestation in the Brazilian Amazon, a 72% reduction by 2018[31]. This significant reduction, substantially changed the distribution of emissions among different Brazilian sectors. In 2005, 70% of Brazilian emissions originated from land use change and forests sectors, and this significantly reduced to 27% by 2010. In contrast, the agricultural sector increased from 14 to 32% in the same period, and energy showed a similar trend from 11 to 29%. (Brazil, 2016).

It is well documented in the in literature, and is further elaborated in Chapter 4, that law enforcement has played a key role in reversing Amazon deforestation since 2004. This success has

[31] Preliminary results of PRODES 2018 available at http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes accessed on 28Mar2019.

been seen as one of the main pillars of a conservation policy, named PPCDAm (Nepstad et al., 2009; Assunção et al., 2013; Hargrave and Kis-Katos, 2013; Arima et al., 2014; Assunção and Rocha, 2014; Dalla-Nora et al., 2014; Nepstad et al., 2014; Assunção et al., 2015; Borner et al., 2015a). However, less attention has been given to possible "side effects" of the intense command and control on reshaping land use dynamics after deforestation.

Meanwhile, land use science has expanded significantly in recent years and taken on more complexity in order to understand the environmental, economic and social aspects that shape land use in a specific region. This understanding should consider local, regional and international aspects, as discussed by Turner et al. (2007). However, the interactions explored at length in the literature rarely consider law enforcement field operations as a factor shaping land use change.

This study aims to evaluate the possible influence of law enforcement on land use change for the significant land-cover types of the Brazilian Amazon, based on data from the most recent official land use mapping in 2014 (Table 2.9): agriculture, livestock(pasture), and secondary vegetation (natural regeneration). First, the evaluation focussed at the municipality level. The evaluation then moves to a more detailed analysis of settlements, and private properties, splitting small and large properties, within the municipalities. Together, these two land use designations represented nearly 65% of land use in 2004 and 2014 (Appendix 9.2 – Table S 2.1).

The analysis considered two groups of municipalities: first, the champions of deforestation, named priority municipalities (PM), and second, the municipalities that have never achieved the criteria to be listed, despite the increased rigour of this public policy during its implementation[32].

In the context of intensified presence of law enforcement on PM, I would predict an increase in the abandonment of areas deforested for future use or speculation on land market, given that a deforested/cleared area triples the value of the land. Once surveillance is present constantly, the risk of being caught and punished for illegal deforestation increases. Also, it was expected that there would be a substantial slowdown, or even a complete halt, on the pace of forest conversion to alternative uses for expansion, namely livestock and agriculture. So, the scarcity of land available for expansion may lead to a change in the business-as-usual land use dynamics and farmer's decision on the best possible use of their land.

Amazon pasturelands currently have room for further intensification (Azevedo et al., 2015; Sparovek et al., 2018), as the occupation is very low, only near 1.2 heads/ha. This is despite a slow but steady

[32] For details of the priority list criteria see section 3.2 in Chapter 3.

increase of in-migration during the last 30 years (Nepstad et al., 2009; Sparovek et al., 2018; IPCC, 2019). Therefore, opening space for improvements with investments in technology, implementation of simple measures, such as pasture rotation, as well as better varieties of cows that can be slaughtered in 2 to 2.5 years against the current 4-5 years. This could spare 50-70M ha of land for annual agriculture to expand (Azevedo et al., 2015). Since soy is the dominant crop in the Amazon region, and it is already at the highest levels and its expansion has to be in areas that are not yet yielding optimally (Meyfroidt et al., 2018). This could lead to spare land and save more forests than the 18-27 million estimated during the Green Revolution (Dobermann et al., 2013). Thus, once this latter possibility has been chosen, an expansion of the agriculture area may become evident, in this case over pasture rather than forests, and a reduction of pasture area with an increased occupation. A different scenario may occur in regions where pasture expansion occurs for land speculation, usually associated with illegal deforestation and land grabbing.

Landowners, however, are mostly profit-motivated, and the land use decision may take a different path, where they can choose to increase the herd without sparing land for agriculture or wild nature, a rebound effect (Lambin and Meyfroidt, 2011). This option may lead to expansion over secondary vegetation/natural regeneration since it is not monitored by the government. The agricultural sector, in turn, with no room to expand onto pasture areas, may also turn their attention to expansion over secondary vegetation/natural regeneration, leading to a possible reduction of natural regeneration. Thus, the restrictions imposed by public policies for conservation, and increased controls over PM, may possibly lead to a change in land use dynamics in the Amazon region.

To date, the Amazon region is a myriad of the middle-range theories of land system change through expansion and intensification (see Meyfroidt et al. (2018)). It is not difficult to identify them in different portions of the Amazon. For instance, the central area of MT is a commodity frontier of soy, capital intensive and market oriented. By contrast, Acre and Rondônia are dominated by smallholders willing to live at subsistence levels. In some cases, however, the smallholders make a profit from their lands, as mixed producers, based on labour inputs and food oriented outcomes for local and regional markets. Meanwhile, Pará state is a mix of subsistence and commercial activities.

Certainly, these changes will not be homogeneous, and will vary by region, scale and land designation: private properties including settlements; small and large properties; public areas of restricted use including Indigenous Lands, PAs including strict protection and sustainable use; and undesignated public lands.

This should lead to further investigations of possible influences on differentiated law enforcement on settlements. These may include small and large properties, considering that most of the law enforcement focused on large deforested areas, is more often associated with large properties. Over the study period, MMA (2018) documented a significant reduction of large deforested areas (> 200ha) and an increasing dominance of small deforested areas (<20ha).

Under this scenario, more pronounced changes in land uses would be predicted for large rather than small properties. There would be more abandonment, possibly more intensification of pasture use and expansion of agriculture over pasture areas. But, the simple presence of law enforcement, might also indirectly affect these smallholders. Therefore, the possible changes towards intensification or expansion may be different for settlements, smallholders and large properties, as the first two are more oriented to produce food for the population and the internal market. Meanwhile, the latter is commodities export-oriented. So, in addition to the municipality level analysis, I will evaluate possible land use change under the presence of intensified surveillance for these three groups separately.

The chapter continues with a short description of the study area, data organization and selection for this specific study, the methods applied to assess the possible influence of law enforcement on AFOLU change at the different scales: municipality, private properties (small and medium-large) and settlements. Then, I will present and discuss the results, closing the chapter with final remarks and conclusions.

5.3 Methods

5.3.1 Study area

The study area for this chapter was restricted to 494 municipalities of the Brazilian Legal Amazon (Figure 5.1), that were covered with over 10% forest in 2004, according to Terraclass mapping, similar to Cisneros et al. (2015) and Koch et al. (2019) who selected 492 municipalities based on Prodes 2002 forests cover (> 10%).

Due to lack of outcome data, the property level analysis will assess 492 and 490 municipalities for small and medium-large, respectively. Meanwhile, 420 municipalities with settlements will be assessed. In all cases, the losses were only in the control group, while the 52 treatment municipalities remain intact.

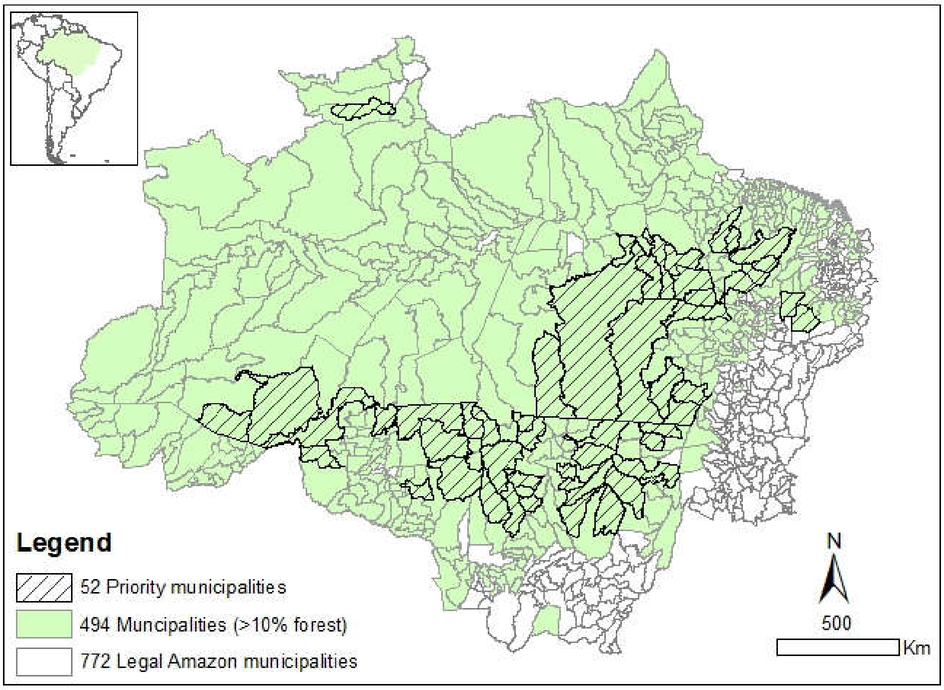

Figure 5.1 – Brazilian Amazon 494 municipalities (green) included in this specific study, highlighting the 52 priority municipalities (stripes). (Source: MMA)

5.3.2 Data

For the analysis of this chapter I combined multiple data sources of the Amazon region (see Chapter 3) to make a panel dataset, from 2004-2014:

- fines from the Brazilian Environmental agency (Ibama);
- annual deforestation rates, land cover and land use change; climatic data including rainfall and temperature (Inpe);
- agriculture and livestock loans (Brazilian Central Bank);
- CAR – rural environmental property registry (Brazilian Forest Service);
- priority municipalities and protected areas (MMA);
- indigenous lands (FUNAI);
- settlements (INCRA);
- heads of cattle, soybean, technical assistance, GDP, companies, population, Gini index, land value, roads and municipality area (IBGE).

Also, the study is restricted to the three main land cover types: agriculture (6%), pasture (62% - 4 classes aggregated into the two groups of clean and dirty pasture), and secondary vegetation/natural regeneration (23%), covering 85-94% of the mapped area along the 2004-2014 period (Table 2.9).

For the property level assessment, I accessed CAR and followed a simplification of the Brazilian Forest Act (Brazil, 2012a) property size classification: small properties (≤ 4 fiscal modules) and the aggregation of medium and large properties (> 4 fiscal modules) in the single category of large properties. This resented a reasonable split as the Brazilian government agricultural policies are generally differentiated only for small farmers.

Use of CAR was restricted to private properties (over 90% of all registries), and have not included settlements and Quilombola territory[33] to reduce possible overlaps. Moreover, the settlements' spatial information came directly from the INCRA database.

Likewise, the CAR registry still has overlapping properties[34]. To overcome this problem I opted to dissolve the property borders within each category of property size, whether small or large, and in

[33] Descendants of slaves areas

[34] The CAR overlapping check phase is still in progress, therefore it is most safe and conservative to use only the dissolved polygon of each small and the aggregated large category within each municipality.

each municipality to avoid double counting. Only after this pre-processing CAR was overlaid with land use maps.

Last but not least, CAR only became an information source for property level analysis after 2012, which might not yet be considered appropriate here, since it was consolidated only after the treatment threshold (2008). However, the land tenure structure of private properties has not changed significantly during this century (Appendix 9.5 – Table *S* 5.3), based on the analysis of IBGE agricultural census. Therefore, this will not result in any significant loss to the results of the property analyzes.

5.3.3 Empirical strategy – Difference-in-differences with entropy balancing.

I combined Difference-in-differences with entropy balancing (Hainmueller, 2012), to assess the possible influence of law enforcement on land use change after the PM policy, comparing priority municipalities (PM) as treatments, with non-priority municipalities (NPM) as controls (see Chapter 3).

This study expanded on Koch et al. (2019) and other studies (D'Antona et al., 2006; Lorena and Lambin, 2009) by evaluating changes in AFOLU at the property level and settlements. This enabled an assessment of what type of land tenure might be most influential on land use changes identified at the municipal level. Nevertheless, I also checked whether or not the municipal level analysis has captured changes in AFOLU that may have occurred at finer scale, like private properties and settlements, within the municipal borders.

Also, pastureland was broken down into clean and dirty pasture in order to assess possible changes in AFOLU for these two categories. Thus, I followed a simplification of the TerraClass land use mapping categories (Appendix 9.2 – Table *S* 2.2), where: clean pasture refers to herbaceous pastures, and dirty pasture is the sum of the other three categories of pasture, including: pasture with exposed soil; shrubby pasture; and pasture with vegetation regrowth.

I started by defining the outcome variables, namely area under annual agriculture or croplands, area under pasturelands, and natural regeneration area, the main land uses after deforestation. Next, in order to establish a well-balanced control group based on pre-policy characteristics, I identified an initial group of variables in the literature for their possible relation or influence on land use change, in the context of law enforcement intensification on the PM (Appendix 9.5 – Table *S* 5.1). Thus, Table

5.1 presents a summary of the outcomes and selected pre-policy variables, checked for any severe signs of multicollinearity (VIF).

Table 5.1 – Statistics summary of the outcome variables, selected variables for the entropy balance pre-processing (mean, SD) and the Variance Inflation Factor (VIF) test result for severe multicollinearity.

Variables	**Control (N=442)**		**Treatment (N=52)**		**VIF****
Outcomes	**Mean**	**SD**	**Mean**	**SD**	
Natural regeneration	0.87	1.35	0.47	0.46	
Annual crops	0.13	0.53	0.43	0.79	
Pasture	-0.09	1.45	0.55	0.95	
Deforestation	-0.09	0.24	-0.29	0.32	
Pre-policy variables					
Municipality area (thousand km2)	7.80	14.77	17.92	24.77	1.23
Population density (2007)	29.04	158.64	3.00	3.09	2.04
Deforestation rate 2002 per municipality area	0.01	0.02	0.02	0.01	1.07
Deforestation rate 2003 per municipality area	0.01	0.02	0.02	0.02	1.46
Deforestation rate 2004 per municipality area	0.01	0.01	0.02	0.01	1.29
2003 Fines(N) per deforested area (km2)	1.12	6.23	0.18	0.26	1.52
2004 Fines(N) per deforested area (km2)	1.15	4.71	0.16	0.20	1.60
2005 Fines(N) per deforested area (km2)	2.41	11.22	0.31	0.47	2.39
Agricultural loans 2004 (cattle and agriculture) (Million R$)*	12.60	40.51	33.05	40.01	1.66
Soy price per hectare in 2005 (Tousand R$)	0.44	0.88	1.11	1.12	1.08
Total GDP 2004 (Million R$)*	0.49	2.96	0.52	1.06	1.24
Forest share 2004 (TerraClass)	0.46	0.29	0.63	0.19	1.42
Non-forest area share 2004	0.12	0.20	0.08	0.11	1.35
Strict Preservation Protected Areas share (2004)	0.03	0.10	0.02	0.04	1.44
Sustainable use Protected areas share (2004)	0.04	0.12	0.02	0.05	1.44
Indigenous Lands share (2004)	0.07	0.15	0.16	0.20	1.67
Settlements share (2004)	0.08	0.13	0.05	0.10	1.43
Rainfall (mm)	1,876.46	383.77	1,899.09	350.59	1.36
Temperature (max) for the hottest quarter (^{o}C)	26.59	1.02	26.12	0.73	1.58
Number of roads junctions	38.53	49.32	115.60	92.34	1.20

* Values deflated to Jun/2016 in Brazilian Reais (R$) using the General Prices Index (IGP-M, brazilian acronym)
** Significant values > 5.00 (analysis performed in Stata 15)

The next step was the entropy balance, the pre-processing technique. The balancing was restricted to a limited number of covariates that were shown to predict treatment: the share of PAs; share of indigenous lands; share of settlements; share of forest; agricultural loans; soy price; accessibility; law enforcement intensity; and climatic variables. Once the balancing is achieved, the selected control and treatment were evaluated for the difference-in-differences.

5.4 Results and Discussion

The results confirm most of the predictions of the influence of law enforcement on land use change, particularly in the context of decoupling conservation initiatives from agricultural expansion suggested by previous analyses (Nepstad et al., 2009; Macedo et al., 2012). Intensification of law enforcement significantly influenced the decrease in forest loss in PM for all outcomes, confirming the findings of Chapter 4. This also suggests that the procedure applied in this chapter is acceptable to investigate the possible influence of law enforcement on land use changes. Likewise, Table 5.2 presents significant results for the three main land uses.

As a result, the following paragraphs will present and discuss the main findings of this observational study for the three main alternative land uses. Complemented by a land use transition matrix analysis for all levels (municipality, CAR and settlement) of the outcomes, for the pre (2004-2008) and post (2008-2014) policy periods, separated in the two groups: PM and NPM. The land use transition matrix will help shed light on the source of land cover for the expansion/reduction of the land uses of interest, represented by their percentage, in order to compose the area of agriculture, pasture and natural regeneration in 2008 (pre-policy) and 2014 (post-policy) (Table 5.3-5.5).

Overall, deforestation has not been completely halted, so the area of the main land uses after clearing has increased in absolute terms during the study period 2004-2014 (Table 5.3-5.5). This is reflected in the main results of the outcomes, whether significantly or not, except for dirty pastures. And, of course, for deforestation that instead presented reductions (Table 5.2).

Table 5.2 – Difference-in-differences with entropy balance estimates.

DID outcomes	Municipality	CAR medium &large (ml)	CAR small (s)	Settlements
Deforestation	-157.10***	-111.14***	-33.57***	-16.96*
	(24.78)	(18.69)	(6.59)	(7.11)
Clean pastureland	426.07**	205.00*	47.49	126.45**
	(141.51)	(91.29)	(30.17)	(42.09)
Dirty pastureland	-30.92	-37.67	74.49	11.59
	(51.57)	(25.87)	(39.58)	(22.38)
Annual cropland	168.03**	146.43**	21.02	-8.05
	(67.91)	(56.65)	(12.34)	(7.62)
Natural regeneration	189.84***	131.72***	34.41*	1.76
	(52.15)	(25.71)	(14.93)	(18.58)

Standard error in parenthesis. * p<0.05, ** p<0.01, *** p<0.001

Before presenting and discussing the results, I will highlight the sharp reductions of forest conversion to alternative land uses revealed by the land use transition matrix (Table 5.3-5.5), indistinctly for PM or not. This suggests that the intensification of enforcement actions played an important role in reducing deforestation, as already discussed elsewhere (Chapter 4). Besides, the results for PM policy shows a lower percentage of forest conversion for the post-policy period for all levels (municipalities, CAR small, CAR medium & large, settlements).

Another expected result is the higher percentage of forest conversion for PM before and after the policy implementation and law enforcement strengthening, revealing that PM are very active deforestation frontiers, and also some limitations of the ground inspections (discussed in detail in Chapter 4).

Agriculture

Having said that, the results for annual crops was as expected, and highlighted the significant increase of 168 km2 of annual cropland in PM compared to NPM during the post-policy period. Besides, decomposing by land tenure: settlements and private properties (small and large), it can be seen that large private properties show a significant increase of 146 km2 for PM after treatment. Furthermore, large properties respond for 75% of annual cropland in the Amazon region with a more pronounced increase of 58% for PM compared to 21% for non-priority between 2004 and 2014 (Table 5.3). Meanwhile, small properties and settlements did not in general present significant results (Table 5.2).

Nevertheless, Figure 5.2 presents two further aspects important for annual agriculture in the Amazon. The first relates to the high concentration of agriculture in the state of Mato Grosso, 92% and 86%, in 2004 and 2014, respectively. In addition, in 2014, the state was responsible for 28% of the national soy production (IBGE, 2014). The second important aspect is that this activity more than doubled its area in the same period, increasing from 18 to over 45 thousand km2 (Table 2.9). Furthermore, this activity is not only concentrated in this state, but is also an agglomerated economy in the central area (Figure 2.8).

In addition, the land use transition matrix (Table 5.3) shed light on interesting aspects related to the pre and post-policy periods, and the intensification of law enforcement since 2005 (Figure 3.2).

First, there was an increase in the persistence of the annual agricultural area after policy implementation, an increase from 11-53% in 2008 to 45-71% in 2014 considering all levels, in both groups (control and treatment). However it was invariably higher for NPM.

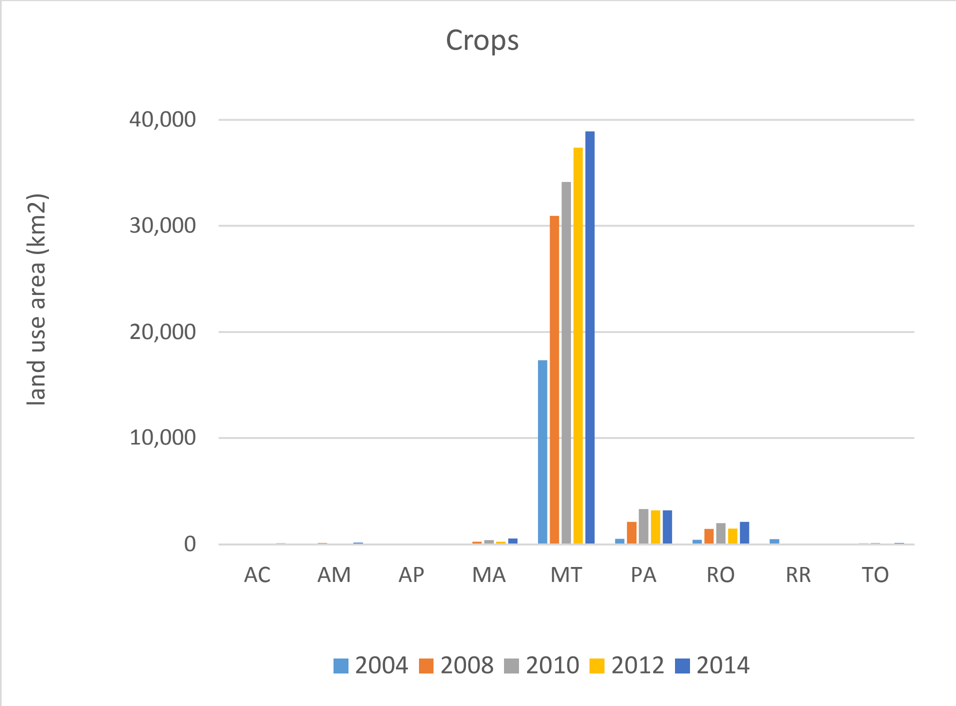

Figure 5.2 – Annual croplands (km2) for the period 2004-2014 presented by the nine Legal Amazon states.(Source: Terraclass (INPE-EMBRAPA))

Second, forest conversion to agriculture reduced drastically, and clean pastures continued to be the main source of area for expansion of annual crops, independent of the status of the municipality whether PM or NPM, in line with the findings of Gollnow *et al*. (2018).

Third, overall, as a result of land scarcity due to a more intense surveillance and law enforcement and less forest conversion, the post-policy period showed an increase in agricultural expansion over dirty pasture. Moreover, as expected, PM also increased its percentage of agricultural expansion over natural regeneration. Meanwhile, non-priority showed a small reduction. These results are encouraging and in line with suggestions of other authors (Barretto et al., 2013; Azevedo et al., 2015; Sparovek et al., 2015; Moutinho et al., 2016) that reducing forest conversion and expanding over areas already cleared is one of the best practices to reduce emissions, spare land for conservation and ultimately achieve the NGOs pledge of 'zero deforestation', all in balance with the desired continued development.

The same trend was observed for all three land tenures within the municipalities, but at different magnitudes. For instance, the results of the land use transition matrix suggested a strong influence of law enforcement on private properties independent of their size. First, the private properties whether small or large, in PM, experience greater reductions of forest conversion compared to non-priority for the post-policy period. In contrast, the cropping area expanded in small (38%) and large

(58%) properties in PM for the post-policy period, by increasing the conversion of dirty pastures and natural regeneration, while clean pastures become more persistent, especially for large properties of PM (Table 5.4) and with less conversion to agriculture in the post-policy period.

Table 5.3 – Annual agriculture transition matrix for the pre and post policy periods. Abbreviations: priority municipality (P), non-priority municipality (NP), agriculture (a), clean pasture (c), forest (f), dirty pasture (p), and secondary vegetation/natural regeneration (s). (Sources: MMA, INCRA, IBGE e Terraclass (INPE-EMBRAPA))*

		Agriculture											
		2004 → 2008						2008 → 2014					
2004		aa	ca	fa	pa	sa	Total 2008 (km2)	aa	ca	fa	pa	sa	Total 2014 (km2)
Municipality	NP	0.52	0.25	0.04	0.03	0.05	23,933	0.67	0.20	0.01	0.05	0.04	28,676
	P	0.41	0.27	0.09	0.04	0.03	9,920	0.56	0.26	0.01	0.10	0.05	15,303
CAR small	NP	0.53	0.27	0.04	0.03	0.04	4,824	0.71	0.16	0.01	0.04	0.04	5,644
	P	0.44	0.23	0.08	0.06	0.03	1,376	0.62	0.19	0.02	0.09	0.06	1,904
CAR large	NP	0.53	0.24	0.04	0.03	0.05	16,911	0.66	0.22	0.01	0.05	0.04	20,521
	P	0.41	0.28	0.09	0.04	0.03	8,130	0.55	0.27	0.01	0.10	0.05	12,881
Settlements	NP	0.27	0.44	0.06	0.06	0.08	1,107	0.45	0.30	0.03	0.08	0.05	1,825
	P	0.11	0.32	0.20	0.14	0.02	316	0.45	0.28	0.06	0.10	0.08	307

* The percentages will not sum to 100% since not all land tenure classes are included in the analysis, but only the most important.

These results also showed that agriculture is a persistent land use over the study period, as less than 1% was converted to pastures or abandoned for natural regeneration, according to the land use transition matrix for these two land covers (Tables 5.4 and 5.5, respectively). A reasonable first explanation for agriculture persistence is the 6.4 times higher profit for soy over cattle production (Sparovek et al., 2018).

Furthermore, theories of land use expansion and intensification presented by Meyfroidt et al. (2018) can help understand the pattern developed by annual crops in the Amazon region. Expansion can occur over natural areas, as reported here, to be more intense in the pre-policy period, and drastically reduced after PM policy implementation, or could occupy pasturelands, as Table 5.3 reveals, as the main source for annual crops expansion, independently of the pre or post policy period for both groups (PM & NPM).

In addition, Gibbs et al. (2015) reported the importance of the soy moratorium in restricting the expansion of soy to deforested areas before 2008. This was corroborated by Abiove (2017) who reported that only 1% (47,365 ha) of soy was planted in areas deforested after 2008, and not in compliance with the soy moratorium.

Furthermore, Sparovek et al. (2018) showed that soy expansion in Brazil over the last 30 years occurred simultaneously with consistent increases in productivity. This led to the intensification part presented by Meyfroidt et al. (2018), which displays two major paths: increasing inputs per land unit through technology and/or multiple harvests, and increasing outputs per land unit (yields). In addition, as proposed by Garrett et al. (2018), the literature suggests three potential pathways for agricultural intensification: land scarcity, agglomeration economies and livestock industrialization.

So far, soy in the Brazilian Amazon has developed as a combination of the pathways described in the preceding paragraphs. First, the path of intensification as an agglomerated economy in the central area of Mato Grosso state (Abiove, 2017; Gollnow et al., 2018), mostly guided by agricultural incentives associated with areas of reasonable agricultural suitability (Morton et al., 2006), development of good infrastructure to storage (Frey et al., 2018) and transport (Pfaff et al., 2018) to guarantee competitive prices for exports to meet the growing international demand (Fearnside and Figueiredo, 2015). In contrast, the second path, land scarcity, was shaped by environmental rules, law enforcement and the soy moratorium have imposed restrictions and disadvantages (Macedo et al., 2012; Garrett et al., 2013a; Garrett et al., 2013b; Gibbs et al., 2015; Lisa and Holly, 2016; Kastens et al., 2017; Silva et al., 2017).

Simultaneously, while soy yields have slowed down and practically reached a threshold with the available varieties (CONAB, 2017; Sparovek et al., 2018), double-cropping systems have grown substantially and are currently predominant in Mato Grosso (Dias et al., 2016; Picoli et al., 2018). Moreover, a "third" cycle of planted pasture is becoming popular among farmers to further maximize revenues. So, consolidation is underway (Picoli et al., 2018), and such multiple harvesting systems suggested that croplands are moving in the right direction towards a sustainable intensification of the land system (Thomson et al., 2019).

Pastures

Moving to pasturelands, the difference-in-differences results revealed a significant increase of clean pastures of 426 km2 for PM compared to NPM, as large private properties and settlements, with 205 km2 and 126 km2, respectively. Despite the same increasing trend, small private properties were not significant for clean pastures. In contrast, dirty pastures showed no significant results, and an opposite trend of area reduction for the municipality and large private properties. Meanwhile, settlements and small private properties show an increasing trend with no significant results. (Table 5.2).

The results suggested that the constant presence of law enforcement, and the increased number of fines contribute to changes in the land use dynamic of pastures, especially in the post-policy period, increasing areas of clean pastures, and reducing dirty pastures, in line with Schielein and Börner (2018) findings that better law enforcement is a plausible explanation for an increased share of clean pastures.

In order to complement and augment the difference-in-differences findings, I resorted to the land use transition matrix for pastures to evaluate the main land uses that contributed to the area for pastures in the pre and post treatment periods (Table 5.4). The results are illuminating and confirmed some predictions, indicated some changes, and supported drawing important considerations and concerns about this activity in the Amazon.

First, the pasturelands transition matrix (Table 5.4) showed an increase of clean pastures area after policy implementations of 13.2% and 9.4% for PM and NPM, respectively. Moreover, CAR small, CAR large and settlements followed the same increasing trend. By contrast, dirty pastures lost an impressive 24% of the area in PM, and 4.9% for NPM. At the finer scale, private properties and settlements in PM revealed the same trend of reducing dirty pastures. In turn, NPM small private properties and settlements showed a slight increase, while large private properties reduced in area by 16%.

Second, as expected, direct conversion of forests to pastures decreased substantially after the policy implementation in 2008, most markedly for dirty pastures in the PM. However, the percentages of forest conversion to pastures were still high compared to agriculture. In contrast, as predicted, there was an increase of natural regeneration converted to clean pastures from 3% in the pre policy to 7% in the post policy period. Plausible results were due to land scarcity forced by law enforcement and the fact that natural regeneration was not the focus and also is not monitored by the government surveillance systems.

Third, clean pastures showed higher persistence of above 53% for both groups, at different spatial levels, from municipality, private property to settlements, before and after the policy implementation, compared to dirty pastures with persistence below 27% for all levels and the two groups. Also it is interesting to highlight that the highest increase in persistence of clean pasture of 8% occurred in large properties of PM. As expected, the results suggests possible intensification of pasture use build on the achievements of Koch et al. (2019) who reported significant gains in livestock productivity after policy implementation for PM.

Moreover, dirty pasture was the main source for clean pastures with small differences for some levels when the pre- and post- periods were compared. At the other end, and in line with agricultural increased persistence in the post-policy period, there was almost no displacement of annual crops to pasture for the entire study period.

Table 5.4 – Clean (c) and dirty (p) pasture transition matrix for the pre and post policy periods. Abbreviations: priority municipality (P), non-priority municipality (NP), agriculture (a), clean pasture (c), forest (f), dirty pasture (p), and secondary vegetation/natural regeneration (s). (Sources: MMA, INCRA, IBGE e Terraclass (INPE-EMBRAPA))*

		Clean Pasture											
		2004 → 2008						2008 → 2014					
2004		ac	cc	fc	pc	sc	Total 2008 (km2)	ac	cc	fc	pc	sc	Total 2014 (km2)
Municipality	NP	0.00	0.68	0.05	0.14	0.03	216,000	0.01	0.68	0.03	0.13	0.07	236,392
	P	0.00	0.61	0.10	0.15	0.03	84,146	0.01	0.65	0.05	0.16	0.06	95,291
CAR small	NP	0.00	0.66	0.06	0.15	0.04	71,921	0.01	0.70	0.03	0.12	0.07	79,563
	P	0.00	0.62	0.10	0.15	0.04	20,569	0.01	0.63	0.07	0.16	0.06	24,936
CAR large	NP	0.00	0.73	0.05	0.12	0.03	94,936	0.02	0.73	0.02	0.13	0.05	99,414
	P	0.00	0.62	0.09	0.15	0.03	52,011	0.01	0.70	0.03	0.15	0.05	54,356
Settlements	NP	0.00	0.58	0.07	0.18	0.04	42,368	0.00	0.62	0.05	0.14	0.07	49,687
	P	0.00	0.53	0.14	0.18	0.04	12,015	0.01	0.55	0.10	0.17	0.06	16,689

		Dirty Pasture											
		2004 → 2008						2008 → 2014					
2004		ap	cp	fp	pp	sp	Total 2008 (km2)	ap	cp	fp	pp	sp	Total 2014 (km2)
Municipality	NP	0.00	0.38	0.11	0.25	0.09	70,257	0.01	0.38	0.06	0.22	0.18	66,828
	P	0.00	0.29	0.24	0.23	0.09	30,450	0.01	0.41	0.09	0.25	0.14	23,098
CAR small	NP	0.00	0.38	0.11	0.27	0.10	20,088	0.00	0.42	0.07	0.21	0.17	20,543
	P	0.00	0.31	0.23	0.23	0.09	7,081	0.00	0.38	0.12	0.22	0.14	5,599
CAR large	NP	0.00	0.45	0.11	0.23	0.08	25,782	0.01	0.46	0.04	0.24	0.15	21,685
	P	0.00	0.30	0.24	0.23	0.09	16,749	0.01	0.45	0.06	0.26	0.14	12,427
Settlements	NP	0.00	0.32	0.13	0.27	0.09	15,391	0.00	0.36	0.09	0.20	0.18	16,665
	P	0.00	0.26	0.26	0.26	0.08	4,999	0.00	0.36	0.14	0.22	0.13	4,461

* The percentages will not sum to 100% since not all land tenure classes are included in the analysis, but only the most important.

It is not by chance that pastures dominate the deforested Amazonian landscape. The results presented so far support interesting aspects related to this activity and its connections with law enforcement and the economic model of crime that I will explore in the following paragraphs.

First, the results suggested that law enforcement contributed to livestock intensification, and second, intensification can help reduce land speculation and land grabbing that undermine cattle productivity, following the pathways of land scarcity and livestock industrialization.

It is important to keep in mind that in some circumstances cattle ranching represents “an unproductive profit seeking” to keep control over large portions of land, while waiting for higher land prices when development arrives (Bowman et al., 2012; Garrett et al., 2017). This chain of events finds ground in the economic model of crime (Becker, 1968), which was briefly presented in Chapter 4. Becker stated that as long as crime benefits are higher than the product of crime costs and punishment probability, activities like land grabbing and illegal deforestation will continue. Deterrence is also an important component in the equation of pastures dynamics.

Having said that, the scarcity of land available for expansion imposed by the presence of law enforcement activity has paved the pathway for intensification of the livestock system. However, the recent events involving this policy and law enforcement suggests that they have catalyzed this process in combination with other initiatives, like the beef agreement with the most important slaughterhouses in Pará state. Also, pilot projects implemented by NGOs have shown considerable yields gains by taking some simple measures in the farms. These measures include pasture management and animal feed, that can increase animal production and reduce the time spent in pasture (Santos and Costa, 2018).

For instance, Garrett et al. (2017) reported that ranchers are reconsidering their practices to invest more in intensification, as confirmed in this study. The reduction in forest conversion, and an increase in dirty pastures and natural regeneration were the sources for forming clean pastures after the PM policy. Certainly, the economic attractiveness of crime has been reduced building on Becker’s ideas of the increased costs of crime and increased fear of being caught. For instance, JBS, a global player in the beef market, was fined for buying from embargoed areas in 2017, despite all the information available for checking their supply-chain. This is evidence that offenders still find ways to evade the regulations and continue their illegal operations. Equally this might be related to imperfections of the conservation policies and regulations that create opportunities for producers to elude.

Land speculation is another important aspect of the livestock industry in the Amazon that undermines its productivity and certainly contributes to the slow pace of intensification within this industry. The recurrent land rights problems, land tenure issues and land grabbing in the region have brought instability to landowners who are risk-averse. Sometimes they are aware of the illegality of the land they are buying and using, but others have not been so aware (Bowman et al., 2012). Indeed, land tenure is by far the most important issue to tackle in the Brazilian Amazon, in order to reduce insecurity of land rights and increase the confidence of the private sector to invest.

So, ranchers keep their lands producing, but with extensive cattle ranching, at a low cost, less capital intensive activity and a low risk way of controlling the area (Araujo et al., 2009; Garrett et al., 2017), even when technology and in-put availability has improved (Bowman et al., 2012). The distance to markets was a classical Von-Thünen situation, where more investment in intensification would not pay off. So, as discussed earlier "this represents an unproductive profit seeking arrangement" waiting for development to arrive and to generate profits by selling the land, and not necessarily by producing a commodity (Caviglia-Harris, 2018; Frey et al., 2018).

Meanwhile, especially for small farmers, cattle ranching represents an important and solid activity with low investments and easy to manage with more intensive practices of their herd (Pacheco, 2012). Also, in distant areas of the Amazon region without access to a banking system, cattle are recognized as the Bio-ATM machine for emergencies like income shortfalls and health issues, that farmers can always sell quickly (VanWey et al., 2012). Thus, cattle provide the necessary financial security and are easier to manage compared to crops independent of spatial pattern and property size, despite the lower profits. In other words, cattle ranching has a long tradition in the Amazon frontiers and is spread all over the region, compared to crops that are part of an agglomerated economy in Mato Grosso.

In the literature, most of the strategies to converge and balance agriculture, conservation and restoration, points to an essential action: intensification of agricultural activities (Balmford et al., 2005; Rudel et al., 2009b; Phalan et al., 2013; zu Ermgassen et al., 2014; IPCC, 2019). In the Brazilian Amazon, it can be translated into increased productivity in pasture lands, which are currently at very low levels and slowly increasing. Meanwhile, literature also shows that the issue of intensification still has its effectiveness questioned (Meyfroidt et al., 2018). We cannot be so naive as to propose livestock intensification as the silver bullet for reducing deforestation, or be so simplistic as Lord Nicholas Stern who posits that the Borlaug hypothesis is simply double pasture occupation from one to two heads/ha to save the Amazon forests. As Defries and Rosenzweig (2010) suggest, this is necessary but not sufficient. Merry and Soares-Filho (2017) went further by suggesting that intensification of the cattle-beef system in Brazil may not deliver sustainability goals. Indeed, social, economic and environmental factors are interconnected and part of this complex equation or, if you prefer, this huge puzzle.

First, the beef sustainability model must be implemented hand-in-hand with consistent territorial governance to avoid illegal land grabbing. As reported above and according to Bowman et al. (2012) simulations suggests it is most profitable for extensive livestock, with large speculation, normally in border regions, following the Von Thünen model, and where it is only marginally profitable to raise cattle.

Second, environmental and land tenure surveillance must be present to ensure the effectiveness of intensification and that it fulfills its role of sparing lands for agriculture, other uses, and conservation, rather than being used to expand pastures on an illegal basis. In summary, cattle are not profitable everywhere in the Amazon, as highlighted by Bowman et al. (2012). Cattle require consolidated frontiers, closeness to markets, and well-established infrastructure. When these are in place, cattle may make the profit-levels that would convince landowners to implement intensification via new technologies, but with some extra costs for their production system.

Third, in the literature, intensification is also viewed with caution by researchers who point out the risk of a rebound effect (Sparovek et al., 2015; Meyfroidt et al., 2018; Sparovek et al., 2018). Higher productivity and efficiency gains may result in more profits and consequently more expansion, in contrast to the desired effect of sparing land to balance with other activities and conservation, jeopardizing the strategy of governments, NGOs and other stakeholders. Additionally, le Polain de Waroux et al. (2017) points out that policies aiming to increase intensification, also decrease deforestation, and avoid rebound effect, they must consider and depend on a balance of penalties and rewards for intensification.

Natural regeneration

The difference-in-differences results for natural regeneration confirmed the predictions, and revealed a significant increase of 190 km2 for PM after the policy, as large and small private properties, 132km2 and 34km2, respectively. In turn, settlements do not show significant changes. These results suggests that law enforcement is playing an important role in the recovery process of natural areas in active deforestation frontiers in the Brazilian Amazon.

Moreover, Figure 5.3 supports interesting aspects of natural regeneration dynamics over the study period. First, Pará state, the champion of deforestation, is also, by far, the state with the largest area of natural regeneration. Second, the area of natural regeneration rapidly increased during the study period for the five most important states in terms of deforestation, namely Pará (PA), Mato Grosso (MT), Rondônia (RO), Maranhão (MA) and Amazonas (AM). Third, after a sharp increase, Mato Grosso and Pará had stabilized their areas of natural regeneration by 2010 and 2012, respectively. These results were indicative of a change in land use dynamics after increased law enforcement. Where deforestation dropped, agriculture and persistence of clean pasture increased. Furthermore, the conversion of natural regeneration to these two alternative land uses also increased to avoid government surveillance and to help fulfill the needs of area expansion and market demands, concomitant with the intensification process described earlier in this section.

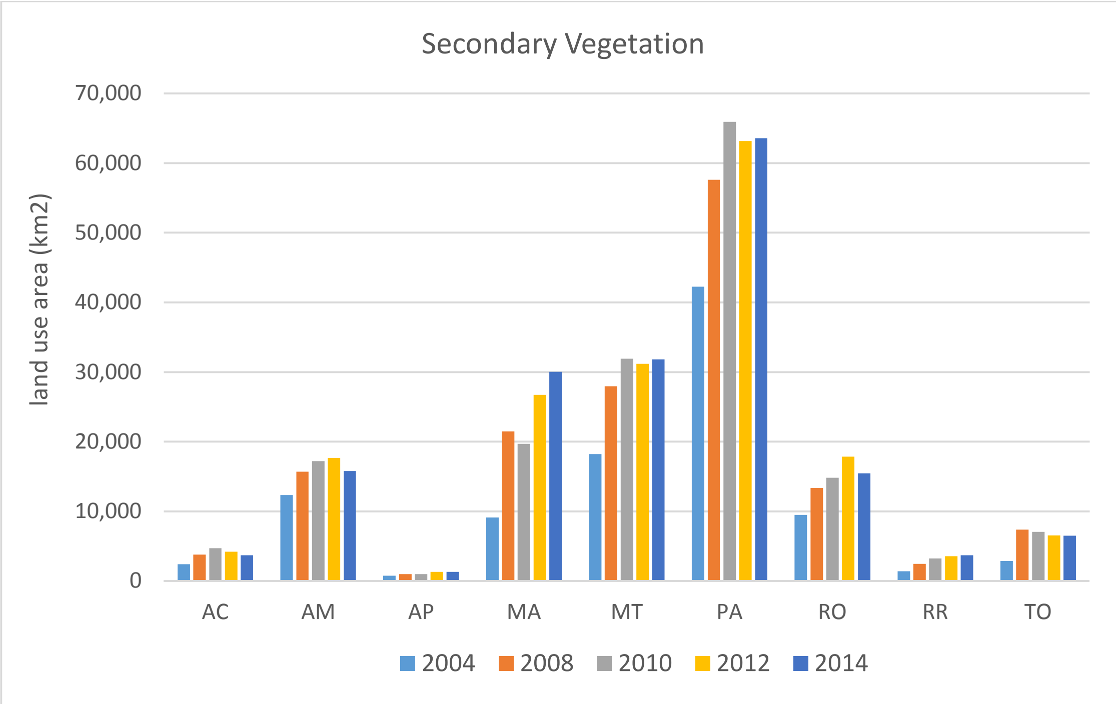

Figure 5.3 – Natural regeneration (km2) for the period 2004-2014 presented by the nine Legal Amazon states. (Source: Terraclass (INPE-EMBRAPA))

The land use change transition matrix for natural regeneration (Table 5.5) sheds light on important aspects. First, NPM support nearly four times the area of natural regeneration compared to PM. This is in line with results from the literature that show natural regeneration, as part of the fallow period, more often occurs in consolidated frontiers in the eastern and southern boundaries of the Amazon (Figure 2.8), where it can be observed in Rondônia, eastern Pará and western Maranhão, as well as spreading into central-north of Mato Grosso.

Second, forest conversion to natural regeneration was as expected, being more intense in PM, private properties and settlements before and after the policy change. At the same time, it has clearly declined in the post-policy period, providing consistent information on reducing forest loss and the possible influence of law enforcement, presented in Chapter 4.

Third, dirty pasture is the most important source of natural regeneration, but with opposite trends when PM and NPM were compared in the post-policy period. In PM the abandonment of productive areas increased for private properties and settlements, while abandonment reduced in NPM, private properties and settlements. This change might result from the presence of law enforcement, with fines and embargoes, reducing the possibility of using the land illegally, and forcing offenders to abandon the area, even only temporarily, until law enforcement is relaxed. However, it could also have been the fallow period (Moran et al., 1996; Evans et al., 2001; D'Antona et al., 2006; Pacheco, 2012), a very common practice in the Amazon to recover the soils for the next cycle, and to be explored in more detail in Chapter 6. Meanwhile, clean pasture was the second source of natural regeneration with increased participation in the post-policy period, but differently from dirty pastures, with no distinction between PM and NPM.

Finally, the post-policy period produced an increase on the persistence of natural regeneration, a very important topic for the Brazilian NDC, a commitment to restore 12M ha by 2030 that will also be explored further in Chapter 6.

Table 5.5 – Natural regeneration transition matrix for the pre and post policy periods. Abbreviations: priority municipality (P), non-priority municipality (NP), agriculture (a), clean pasture (c), forest (f), dirty pasture (p), and secondary vegetation/natural regeneration (s). (Sources: MMA, INCRA, IBGE e Terraclass (INPE-EMBRAPA))*

		Natural Regeneration											
		2004 → 2008						2008 → 2014					
2004		as	cs	fs	ps	ss	Total 2008 (km2)	as	cs	fs	ps	ss	Total 2014 (km2)
Municipality	NP	0.00	0.10	0.09	0.18	0.48	109,656	0.01	0.11	0.05	0.13	0.56	120,176
	P	0.00	0.10	0.16	0.16	0.46	28,461	0.00	0.14	0.07	0.19	0.51	33,160
CAR small	NP	0.00	0.12	0.09	0.20	0.47	26,095	0.00	0.15	0.04	0.15	0.55	26,931
	P	0.00	0.12	0.18	0.16	0.43	5,846	0.00	0.16	0.11	0.19	0.46	6,612
CAR large	NP	0.00	0.14	0.08	0.18	0.48	34,092	0.02	0.14	0.03	0.15	0.58	35,864
	P	0.00	0.11	0.15	0.16	0.47	16,349	0.00	0.15	0.04	0.19	0.55	18,406
Settlements	NP	0.00	0.10	0.10	0.20	0.42	21,148	0.00	0.11	0.09	0.14	0.51	24,064
	P	0.00	0.09	0.23	0.16	0.40	3,526	0.00	0.14	0.13	0.20	0.42	3,992

* The percentages will not sum to 100% since not all land tenure classes are included in the analysis, but only the most important.

Settlements

Land use changes in settlements are of considerable concern as they have shown a steady increase on deforestation in recent years. This has occurred despite all the law enforcement undertaken to reduce and avoid it, which I started to discuss in Chapter 4. Here, I will continue to explore some other important aspects related to land use change.

Settlements, in the Brazilian sense (see Section 4.4.1), have been the subject of many studies that seek to investigate the dynamics of occupation and land use in the Brazilian Amazon. They have been implemented for a long time. Since the early 1960s, they have been part of the government strategy to occupy the Amazon region and reduce land disputes over increasingly expensive lands in other regions of the country, especially the southeast. Thus, the landless families in the south-southeast and northeast regions (the latter, due to droughts and extremely arid regions) were taken to colonization projects in the Amazon, mostly sponsored by the federal government, but also by private projects. These settlements vary greatly in their form from: fishbone to dendritic; and in their different biophysical conditions of soil, slope, rain, rivers, size of initial lots, origin of the first colonizers, different levels of accessibility, financing and technical support of government agencies, distinct land management practices from agroforestry, slash-and-burn agriculture, pasture, mechanization (D'Antona et al., 2006). Thus, the socio-economic and environmental trajectories are quite different, resulting in different patterns of forest fragmentation and land use change.

Moreover, settlements impose internal dynamics on land use change. As the land became more valuable in certain settlements, usually closer to the markets, some settlers saw the opportunity to sell at higher prices and move to more distant settlements, away from markets and into pristine forest where lots are cheaper. It was a way to make a profit from selling land instead of agricultural revenues. In turn this has led to a re-concentration of land in settlements into large properties and to a certain extent depriving the land of the original purposes of these settlements.

Furthermore, urban migration also contributed to re-concentration, when less capitalized families, were unable to invest in the machinery required for annual crops (Frey et al., 2018), and instead end up selling their lots to more capitalized farmers, before moving to urban areas. Likewise, urban migration includes issues for the younger generations of families who have sought better opportunities in the cities. This is also a way of providing financial support to maintain the rural property through remittances, as reported by Soler et al. (2009). This process was seen more often in older settlements, as a result of family aging, and migration of Youngers, decreasing the availability of labour.

Finally, re-concentration is a determining factor in the process of deforestation (Verburg and Soler, 2010). However, internal settlement dynamics of aggregation and re-concentration are difficult to derive only from studies like this, based on remote sensing, since many of these contracts of aggregation and re-concentration are not officially registered. As a Brazilian expression notes: “drawer contracts” (contratos de gaveta), in which only the buyer and seller know about the transaction.

5.4.1 Study limitations

My initial assumption was that CAR properties would remain under the same ownership throughout the study period from 2004-2014, as outlined in Section 5.3.2 and Appendix 9.5 – Table *S* 5.3.

However, it has been almost impossible to track all changes in properties during that period. Nevertheless, this problem might be overcome in the near future if CAR is fully implemented and farmers keep their registry updated in compliance with environmental legislation, and if they take part in the clean supply chain for the most important commodities. However, the CAR registration process can generate uncertainties, as it is self-declaratory, subject to property overlaps that can only be resolved during the validation phase rather than completed in the timeframe of executing this study. But most important of all, CAR does not solve land tenure issues.

Another important limitation is related to land renting that cannot be captured by remote sensing analysis. These “drawer contracts” are not limited to settlements, and are a common practice throughout the region. Somehow, they appear a “win-win solution”, where the small landowners unable to capitalize and mechanize their production, simply rent their lands and can profit without having to work. At the same time, capitalized farmers make their profits by implementing mechanized agriculture on rented lands. In turn, this might result in miss-interpretations of the responsibility for deforestation and land use changes, mistakenly blaming certain producer groups such as small producers. Such situations demand field work through interviews for more accurate mapping and triangulation. It is a fact that the agricultural census can map some of these phenomena, but when it is illegal, it will hardly be captured through official means.

Third, the land use and land cover change series is not long enough, and the results will be limited. Fallow periods can last for as long as 20 years, before farmers return to the same land to start new agricultural activities. A more comprehensive analysis would benefit from a longer land use change time series that could reveal different trends over the long term.

Certainly, all the complexity involved with land use change in the Brazilian Amazon has not been captured in this 10-year study. Thus, I tried to cover the most representative factors identified in the literature. However, other factors may have come into play, if not be directly affected by deforestation and land use, at least indirectly. For instance, experience in the field suggests possible relations with drug trafficking financing deforestation and *vice-versa*, valuable timber and land grabbing raising money for international drugs trafficking. The same could apply for valuable minerals like gold, diamonds and the illegal market, raising and laundering money through land and cattle acquisition. A limited livestock control creates a favorable environment for illegalities in this supply chain. Some initiatives that have a better control of the supply chain are trying to reverse the situation.

This study did not aim to model and predict deforestation and land use change for the coming decades. As the models have not yet properly predicted the sharp declines in deforestation and land use changes (Dalla-Nora et al., 2014), the next generation of models must pay attention to adding scenarios where good governance and policies can have a positive effect and reduce forest loss. As suggested by Meyfroidt et al. (2014 p.9): “Simulation models greatly contribute to this goal, but empirical approaches are also needed to improve the design, calibration, validation and interpretation of simulations.”

5.5 Conclusions

Conservation policies based on law enforcement have reshaped land use systems in the Brazilian Amazon, as predicted at the start of this study. Certainly, this has not been achieved alone but in combination with other policies and initiatives. The results have shown that the PM policy was launched at the correct time, and made it possible to reverse the resumption of deforestation and continue on the path of reducing forest losses. In addition, it stimulated, and to some extent, forced changes in the behavior of landowners to make better use of deforested lands, due to land scarcity, with clear signs of improvement in soy and meat production systems. Indeed, these changes have a long way towards achieving a balanced landscape.

This study has shown that intensification of law enforcement became a stronger component in the equation of farmers' agent based land use decisions, where many activities still remain illegal. This current scenario will only be reversed with more environmental compliance, and a substantial reduction in the level of illegal agricultural activities and land speculation. Otherwise, law enforcement will continue to place high weights on the agent investment decision-making process. Furthermore, the relaxation of law enforcement could reverse the downward trends in forest loss. Indeed some authors argue that current reductions are circumstantial (Schmitt, 2015).

A consistent and permanent change will require a cultural change, in combination with strong governance and a policy mix to respond to specific environmental, socio and economic demands on the area of interest. Thus, while illegality still prevails, environmental and land tenure law enforcement will be mandatory in order to: i) ensure the effectiveness of a sustainable intensification; ii) reduce forest loss; and, iii) fulfill the role of spare lands for conservation, agriculture and ultimately a balanced land use system (Schielein and Börner, 2018).

Moreover, as part of PPCDAm, law enforcement has operated strongly in different parts of the supply chain for soy, beef and timber. Interventions in the field include: embargoes; fines, as at soy storages and beef slaughterhouses; stopping traders from transporting or commercializing illegal commodities; investigations on bank loans financing illegal activities; and unauthorized area clearances. In summary, these different operations have focussed on the supply side of the land use framework, from avoiding illegal clearing lands, or land grabbing to selling and exporting. On the demand side, interventions by NGOs have helped to create *a momentum* in important forums, like Consumer Goods Forum. Such fora can put pressure on retailers in the European Union to impose restrictions on commodities without a clean and sustainable deforestation supply chain or at least a more responsible supply chain.

Traceability of the full supply chain or custody chain is a necessary tool for timber and must be part of the solution, providing transparency and confidence to all players and stakeholders involved in producing and consuming forest-friendly products, like TRASE initiative[35]. In future, special attention should be paid to the Chinese market, which is a fast growing importer of Brazilian commodities (Fearnside et al., 2013; Fearnside and Figueiredo, 2015)

This chapter has explored the impact of environmental law enforcement on land use reshape. The next chapter will focus the investigation on a specific aspect of land use: the persistence of natural regeneration along the study period.

[35] https://trase.earth/

6 Law enforcement and persistence of natural regeneration

6.1 Abstract

Brazil has recently adopted policies based on command and control that have greatly reduced forest loss in the Amazon region by 82% (2004-2014). However, much less attention has been paid to forest natural regeneration, even though it has been recognized as a global environmental priority for this century. During the same period, natural regeneration has increased by 72%, reaching 173,387 km2, in 2014. Furthermore, 41,426 km2 of natural regeneration persisted for ten years, all during the study period. It is not clear what is driving the persistence and substantial increase. Therefore, this study seeks to investigate if this persistence could be an additive effect of the environmental police actions against deforestation. The results suggest a positive effect of command and control on the persistence of natural regeneration. This observation has important implications for Brazilian climate change policies and restoration commitments under the Paris Agreement. Furthermore, it could represent a substantial contribution for the global restoration targets established at CBD, Bonn Challenge and New York Declaration on Forests.

6.2 Introduction

The control of tropical forest loss presents one of the greatest environmental challenges of all time (Fearnside, 1983; Hecht, 1985; Hecht, 1989; Hecht, 1993a; Moran, 1993; Nepstad, 1997; Angelsen and Kaimowitz, 1999; Barbier et al., 2001; Soares-Filho et al., 2004; Fearnside, 2005; Soares-Filho et al., 2005; Kirby et al., 2006; Soares-Filho et al., 2006; Brondizio and Moran, 2008; Nepstad et al., 2009; Taitson, 2011; IPCC, 2014a; De Souza and De Marco, 2015). In Brazil, policies adopted have greatly reduced forest loss in the Amazon region, and led the country to becoming a global leader in climate change mitigation (Tollefson, 2012; Hansen et al., 2013; Nepstad et al., 2014; Tollefson, 2015). At the same time, in 2010, Brazil became the third major exporter of agricultural commodities (Laue and Arima, 2014). A stimulating contrast of conservation and production.

However, much less attention has been paid to the role of natural regeneration in deforestation (Bowen et al., 2007; Rodrigues et al., 2011), which has been recognized as a global environmental priority for this century, to reverse human-made transformations of tropical forests (Hobbs and Harris, 2001). Moreover, a meta-analysis of land use change reports that natural regeneration is expanding in tropical areas in Asia, Africa, and Latin America (Rudel et al., 2009a).

Restoration has generally been seen as a more expensive and less effective strategy to protect biodiversity, natural resources and sinking carbon stocks, compared with forest protection. However, in some places, especially in highly fragmented landscapes, restoration is the most plausible solution. Within restoration methods, natural regeneration is a low-cost option (Chazdon et al., 2017).

Ambitious goals have already been outlined in Aichi Target 15 to restore 15% of degraded ecosystems by 2020 (SCBD, 2010b), in the 2011 Bonn Challenge -150M ha by 2020 (IUCN, 2011), and in the 2014 New York Declaration on Forests - 350M ha by 2030 (UN, 2014). In the national context, the Brazilian NDC has an ambitious commitment to restore 12M ha of tropical forest. So far, the scenario is changing for the good, at least among the commitments.

In Brazil, Rodrigues et al. (2011) urged that restoration should be scaled up from hectares to square kilometres, thereby taking a broader perspectives of the landscape. This is particularly important for the recovery of degraded land, and not just for wider aims than for reforestation or carbon sink purposes. It is also important for biodiversity, using the Atlantic Forest Restoration Pact Initiative as a laboratory.

In 2005, Asner et al. (2009) found that 1.2% of global humid forests were secondary regrowth (235,000 km2). In 2014, Inpe (2016b) found similar results for the Amazon, in which 1.2% (41,426 km2) of the Amazon's tropical forests comprised ten years' persistent natural regeneration, equivalent to 24% of the total area mapped as natural regeneration. Natural regeneration also showed a sharp increase of 72% in ten years, reaching 173,387 km2, in 2014. However, it is not clear what is driving the abandonment of lands (Laue and Arima, 2014), and consequently the persistence of natural regeneration. Therefore, this study seeks to investigate if it could be a co-benefit of the environmental police actions against deforestation.

In the climate change mitigation equation, forest restoration is critical to carbon sinks and for biodiversity conservation (Shoo et al., 2013). SCBD (2003) estimated in 60-87 GtC the potential mitigation delivered by afforestation, reforestation, avoided deforestation and degradation, until 2050. However, until very recently, 'forest restoration has generally been 'below the radar' in the tropics' (Hecht and Saatchi, 2007 p.670), and requires further study. Hecht (2010) reported many cases of forest restoration under very different circumstances, trying to persuade and revert the catastrophic emphasis on deforestation in the tropics.

Market globalization and the technological advances in agriculture also probably contribute to forest restoration. The large-scale (high concentration of lands) and highly mechanized activities in rural areas have put the small farmers at a disadvantage to compete in the globalized economy. The result has been the abandonment of their land and migration to urban areas, a phenomenon identified in many different regions around the planet, but especially in the tropics (Lambin et al., 2001; Hosonuma et al., 2012; Smith et al., 2014). Moreover, there are from 1 to 6 billion ha of degraded and abandoned lands worldwide. This is not only because of small farmers, but is a broader phenomenon. In many places, newly cleared lands are cheaper than recovering lands using the soil fertility and chemical inputs. This is an important cause of abandoned land globally, and also in Brazil (Gibbs and Salmon, 2015).

Large scale abandonment of pasture has been a very common practice in the Amazon rainforest since the 1970s` (Nepstad and Uhl, 1991; Nepstad et al., 1996; Bowen et al., 2007; Cramer et al., 2007; Bowen et al., 2009; Rudel et al., 2009b; Morrison and Lindell, 2011). Some fallow cycles have been for a short period, while others are left for long successional periods to allow secondary vegetation to return. Persistence of natural regeneration, as in the case of deforestation, is sensitive to environmental, economic, social, policy and political factors (Moran, 1981; Moran et al., 1994; Zarin et al., 2001; Perz and Skole, 2003b; Pfaff and Walker, 2010; Laue and Arima, 2014). Equally, it is a long-term process that may take from decades to centuries to recover, depending on the management goals for that land (Paula et al., 2017).

For restoration to take place, it is necessary to consider ecosystem resilience, land use history and landscape context, in order to identify the appropriate level of intervention (Bowen et al., 2007; Holl and Aide, 2011). This spectrum runs from simple passive restoration, known as natural regeneration, and letting the forest return naturally after removal of the original disturbance, to active restoration, with different levels of human interventions to achieve the desired goal (Morrison and Lindell, 2011). Active (assisted) restoration is subject to a hot debate on the efficiency and efficacy of the interventions, considering the additional costs involved (Morrison and Lindell, 2011; Zahawi et al., 2014; Bechara et al., 2016; Paula et al., 2017).

Based on this literature review, this study aims to investigate the possible effects of law enforcement on ten years persistence of 41,426 km2 of natural regeneration areas in the Amazon region (2004-2014). These data were revealed by land use change mapping through Terraclass (Inpe, 2016b). Fortuitously, this period coincides with the first 10 years of implementation of PPCDAm. The study adds to the spatial resolution and time series of Laue and Arima (2014), by using the original shapefile from Terraclass rather than a 1km2 grid. Furthermore, it also incorporates three more years (2004-2012-2014) to their 2008-2010 dataset.

The remaining sections of the chapter are structured as follows. First, the study area and data sources are introduced. Second, I present the research design to be adopted in this specific study. Third, I will outline the analysis, results and discussion. Finally, I will close with the final remarks and conclusions on the topic.

6.3 Methods

6.3.1 Study area

In this chapter, the study area consists of the 657 municipalities covered by the Amazon land use and land cover change mapping project (Almeida et al., 2016).

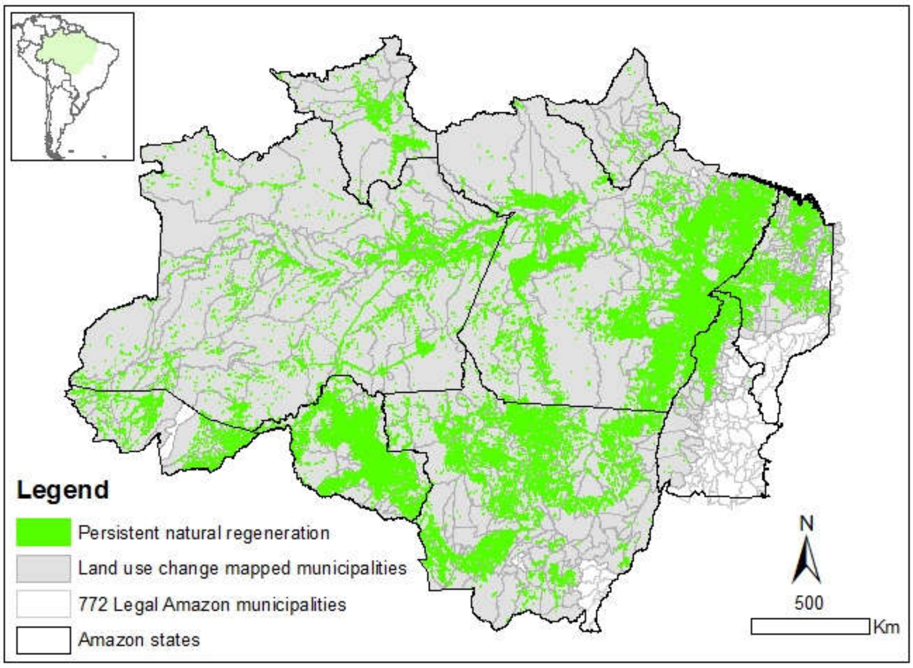

Figure 6.1 – 657 municipalities covered by land use change mapping (Terraclass), highlighting in green the persistent natural regeneration areas. (Sources: IBGE e Terraclass (INPE-EMBRAPA))

6.3.2 Data

All datasets for the analysis in this chapter derive from the period 2004-2014 and comprise the freely accessible sources of the Brazilian Government (Appendix 9.1), already presented in Chapter 4 and repeated here, only for the benefit of the reader.

The critical datasets necessary to investigate the influence of environmental law enforcement on natural regeneration were as follows:

- the fines and embargoes from the Brazilian Environmental agency (Ibama);
- annual deforestation rates (Table 2.2) land cover and land use change, fires hotspots; climatic data including rainfall and temperature (Inpe);
- agriculture and livestock loans (Brazilian Central Bank);
- CAR – rural environmental property registry (Brazilian Forest Service);
- priority municipalities and protected areas (MMA);
- indigenous lands (FUNAI);
- settlements (INCRA);
- heads of cattle, soybean, logging, technical assistance, GDP, companies, population, Gini index, land value, roads and municipality area (IBGE).

6.3.3 Research design and methodology

In this chapter, I applied the same methodology as in Chapter 4 and outlined in Chapter 3 in more detail. Thus, I proceeded with the following steps: data collection and preparation, selection of variables, analysis and hypothese test, to investigate the possible influence of law enforcement on the persistence of natural regeneration.

As in Chapter 4, a group of variables was selected[36] for their possible relationship or influence (+/-) on the persistence of natural regeneration, and checked for no severe multicollinearity (VIF) (Table 6.1). The dependent variable is the persistence of natural regeneration, the independent variable of most interest is fines[37] and the other explanatory variables to control for other factors were the area of persistent agriculture, area of persistent clean pasture, the CAR share area in the municipality, priority municipalities (dummy variable), the non-forest share area, the accessibility measured by all

[36] The initial group of variables are available in Appendix 9.6 – Table *S* 6.1
[37] Detailed explanation of fines x embargoes was provided in Chapter 4 - Section 4.3.3.

roads/highways (paved or not), population density, the percentage of in-migrants in the municipality, rainfall and average temperature (Table 6.1 and Appendix 9.6 – Figure *S* 6.1).

Table 6.1 – Statistics summary of the selected variables for the models (mean and SD.), the possible impact trend on natural regeneration (+ and/or -), and the Variance Inflation Factor (VIF) test result for severe multicollinearity.

Variable name	**Abreviations****	**Obs**	**Mean**	**Std. Dev.**	**Possible impact on natural regeneration**	**VIF***
Natural regeneration persistence (km2)	secveg_per	657	63.054	91.65		
Number of fines	ai_n_04_14	657	107.152	240.110	+	1.48
Non-forest share (%)	Nonforest_share	657	0.201	0.297	+/-	1.13
Priority municipalities (dummy)	mun_prioritario	657	0.096	0.347	+	1.40
CAR area (km2)	car_area	657	2,166	3,966	+	1.22
Agriculture persistence (km2)	agr_pers	657	23.477	158.980	+/-	1.82
Clean pasture persistence (km2)	c_pers	657	218.052	384.016	+/-	1.63
Roads/highways (km)	roads_ibge	657	484.032	588.526	-	2.07
In-migrants (%)	popnaonat2010	657	43.631	22.839	-	1.55
Population density	popdensity2010	657	25.830	131.723	-	1.70
Rainfall (mm/year)	rainfall	657	1,959.038	400.592	+/-	1.05
Average temperature (ºC)	temp_med	657	25.947	1.084	+/-	1.44

* Significant values > 5.00 (analysis performed in Stata 15)
** Abreviations used in Table 6.5

Then, the study continued to the cross-sectional analysis, in a standard specific to general approach (Elhorst, 2010; Golgher and Voss, 2016). As in Chapter 4, the SLM estimated by ordinary least square (OLS) (Appendix 9.6 - Table *S* 6.3) was rejected by Moran and Breusch-Pagan tests. Consequently, the spatial models were estimated. The following Section will present and discuss the spatial models results.

6.4 Results and Discussion

The model results show a significant positive effect of law enforcement on the persistence of the natural regeneration. Thus, in this section, first I will offer an analysis of the distribution of natural regeneration, and then present and discuss the model results in detail.

6.4.1 Natural regeneration persistence distribution

The 41,427 km2 of persistent natural regeneration represents 5.4% of land under use (762,464 km2) and 24% of natural regeneration (173,387 km2) in the Amazon region in 2014. This means that 1 in 4 km2 of natural regeneration is at least 10 years old.

The persistent natural regeneration is mostly concentrated in three states: Pará has the largest area, 14,726 km2 (35%) followed by Mato Grosso 9,039 km2 (22%) and Amazonas 7,176 km2 (17%). (Table 6.2).

Table 6.2 – Persistent natural regeneration distributed by the Legal Amazon states, for the period 2004-2014. (Source: Terraclass (INPE-EMBRAPA))

State	Persistent natural regeneration	
	km2	**%**
Pará	14,726	35.5
Mato Grosso	9,039	21.8
Amazonas	7,176	17.3
Rondônia	4,198	10.1
Maranhão	2,758	6.7
Tocantins	1,372	3.3
Acre	1,167	2.8
Roraima	759	1.8
Amapá	231	0.6
Total	41,427	100.0

Moving to the municipality level, Figure *S* 6.1 (A) (Appendix 9.6) shows that 53% of municipalities had more than 1% of their territory as persistent natural regeneration. Most are located on the consolidated frontier of eastern Amazon, in the arc of deforestation, in line with the findings of Neeff et al. (2006).

Delving further into the property level, 42% of the persistent natural regeneration was in small properties and 58% in medium and large properties. As expected, for the states of Rondônia and

Roraima, 70% of the persistence in natural regeneration were in small properties. At the other extreme, Tocantins and Mato Grosso had 64 and 77%, respectively, in large properties (Table 6.3).

Table 6.3 – Distribution of natural regeneration persistence in small (<4 fiscal modules) and the combination of medium and large properties (≥4 fiscal modules) summarized by states in hectares and percentage. (Source: MMA and Terraclass (INPE-EMBRAPA))

UF	State	small - ha (%)	medium and large - ha (%)
AC	Acre	38,915 (49%)	40,928 (51%)
AP	Amapá	4,454 (48%)	4,786 (52%)
AM	Amazonas	109,920 (50%)	110,366 (50%)
MA	Maranhão	67,534 (51%)	64,924 (49%)
MT	Mato Grosso	161,673 (23%)	554,186 (77%)
PA	Pará	453,903 (42%)	617,776 (58%)
RO	Rondônia	213,988 (71%)	89,276 (29%)
RR	Roraima	25,281 (70%)	10,739 (30%)
TO	Tocantins	32,634 (36%)	59,074 (64%)
	Total	**1,108,301 (42%)**	**1,552,055 (58%)**

The year in which the persistent natural regeneration area (polygons) was cleared revealed that 69% was deforested before 1997. It also showed an increasing trend in abandonments as the analysis moved back in time from 2004: 3.9% in 2003; 5.3% in 2002; 8.5% in 2001; and 12.3% in 2000 (Table 6.4). This agrees with some authors (Moran et al., 2000; Zarin et al., 2001), who claim that farmers use the area for 2 to 3 years and then abandon it due to poor soil quality, their low capacity in investing on soil recovery and a plentiful availability of land elsewhere in natural areas. More recently, in the last 14 years, the presence of environmental law enforcement has imposed some constraints on land availability and this could jeopardize the natural regeneration process and limit soil recovery, with accelerated fallow periods, consequently allowing soils to be degrade faster.

Table 6.4 – Summary of natural regeneration persistence areas by the year of deforestation (%) for the Amazon region. (Source: Terraclass (INPE-EMBRAPA))

UF	state	1997	2000	2001	2002	2003	Total
AC	Acre	2.8	0.0	0.0	0.0	0.0	2.9
AP	Amapá	0.4	0.0	0.0	0.0	0.1	0.6
AM	Amazonas	15.4	1.1	0.4	0.2	0.5	17.6
MA	Maranhão	3.7	0.5	2.1	0.4	0.1	6.7
MT	Mato Grosso	13.7	3.8	1.3	1.6	0.9	21.2
PA	Pará	22.8	4.2	3.7	2.4	1.5	35.4
RO	Rondônia	6.1	2.3	0.7	0.5	0.7	10.3
RR	Roraima	1.2	0.2	0.3	0.1	0.1	1.9
TO	Tocantins	2.9	0.3	0.1	0.1	0.0	3.4
	Total	**69.0**	**12.3**	**8.5**	**5.3**	**3.9**	**100**

6.4.2 The spatial regression model analysis

The results of the SAC model confirmed the positive influence of environmental law enforcement on the persistence of the natural regeneration. There was no need to impose restrictions on the SAC model as SAR and SEM were both rejected (Appendix 9.6 – Table *S* 6.4). Consequently, the following paragraphs will present and discuss the results of the impact evaluation on the natural regeneration persistence using the SAC model (Table 6.5).

Fines

First, the model suggests a significant positive impact of fines on the persistence of passive regeneration by adding 436 ha (124-748) ($p<0.01$) for each additional one hundred fines, considering the 95% confidence interval. Indeed, environmental law enforcement generated a co-benefit beyond curbing deforestation, as detailed in Chapter 4.

The presence of law enforcement generates an increased risk and fear of being caught. As a result, a decline in illegal operations can be observed. If the environment police operations are temporary after they leave, there is always the risk of offenders returning. However, the more permanent presence of the police will, in many cases, force offenders to move to a new and less patrolled area, usually more remote, and away from big centres. Therefore, abandonment of cleared areas increases and natural regeneration may start and persist in these areas, as the results suggest.

New Policies: Priority Municipalities and Rural Environmental Registry (CAR)

Furthermore, two policies implemented by the Brazilian Federal Government: priority municipalities and CAR, also suggest a positive significant contribution to the persistence of natural regeneration, but with different magnitudes.

Table 6.5 – Impact evaluation of natural regeneration persistence SAC model: direct, indirect and total effects (STATA15). (Variables names available at Table 6.1)

	dy/dx	Delta-Method Std. Err.	z	P>z
direct				
Number of Fines (2004-2014)	0.044	0.016	2.74	0.006
Non-forest area	-65.319	9.816	-6.65	0.000
Priority Municipalities	28.479	14.410	1.98	0.048
CAR area	0.005	0.001	3.19	0.001
Agriculture persistence	0.039	0.029	1.34	0.179
Clean Pasture persistence	0.044	0.012	3.78	0.000
Roads/Highways (km2)	0.049	0.012	4.16	0.000
In-migrants in 2010	-0.803	0.188	-4.28	0.000
Population Density in 2010	0.000	0.009	-0.03	0.974
Rainfall (mm/year)	0.009	0.012	0.72	0.469
Average Temp (oC)	7.370	3.845	1.92	0.055
indirect				
Number of Fines (2004-2014)	-0.141	0.110	-1.28	0.199
Non-forest area	211.675	138.855	1.52	0.127
Priority Municipalities	-92.291	69.375	-1.33	0.183
CAR area	-0.015	0.011	-1.34	0.179
Agriculture persistence	-0.127	0.142	-0.89	0.374
Clean Pasture persistence	-0.141	0.110	-1.28	0.200
Roads/Highways (km2)	-0.160	0.114	-1.41	0.159
In-migrants in 2010	2.601	1.551	1.68	0.094
Population Density in 2010	0.001	0.029	0.03	0.974
Rainfall (mm/year)	-0.029	0.045	-0.65	0.518
Average Temp (oC)	-23.884	15.926	-1.5	0.134
total				
Number of Fines (2004-2014)	-0.098	0.104	-0.94	0.346
Non-forest area	146.356	140.466	1.04	0.297
Priority Municipalities	-63.812	64.188	-0.99	0.320
CAR area	-0.010	0.010	-0.97	0.333
Agriculture persistence	-0.088	0.120	-0.73	0.467
Clean Pasture persistence	-0.098	0.105	-0.93	0.353
Roads/Highways (km2)	-0.111	0.111	-0.99	0.320
In-migrants in 2010	1.798	1.607	1.12	0.263
Population Density in 2010	0.001	0.020	0.03	0.974
Rainfall (mm/year)	-0.020	0.034	-0.59	0.558
Average Temp (oC)	-16.514	15.049	-1.1	0.272

First, the PM policy suggested that a significant increase in the persistence of natural regeneration, added 2,848 ha (24-5,672) ($p<0.05$) for listed municipalities. However, this outcome should be viewed with some caution, because this covariate seems to be sensitive to others, where small changes in the inclusion/exclusion of covariates in the model, makes it move from significant to non-significant and vice-versa. Second, CAR can add 0.45 ha (0.2-0.7) ($p<0.01$) of persistent natural regeneration for every 100 ha of CAR added to the system.

The priority municipality list policy suggests a co-benefit for natural regeneration persistence. It appears that law enforcement also contributed to a substantial increase of 75% in natural regeneration, escalating from 100,674 km2 (2004) to 173,387 km2 (2014) (Table 2.9).

CAR still adds little to the persistence of natural regeneration, but as CAR evolves to full implementation in the mid-long term (see Chapter 3), more compliance with the law can be expected. As a consequence, more areas will come formally under passive and active regeneration. The specific decree for CAR established an initial period of two years for landowners to register their properties in the system. However, this has been extended a few times, and currently has no deadline for registering. Once the property is registered, the landowner will know if the property is compliant with the current legislation. If not, the land-owner will have to sign a commitment term as part of the Environmental Regularization Program (PRA, Brazilian acronym). In addition, the landowner has to present a project to restore degraded and altered areas in his property. In doing so, the landowner will be in compliance with the legislation as long as the restoration project is implemented. This has been monitored by the government on a yearly basis, which is mandatory under the Forest Code, and under the penalty of landowners having their registrations blocked and being listed in the government non-compliance public list (Brazil, 2012a; Brazil, 2012b). So far, the results of CAR have been important but not yet very extensive, due to the short interval of 2 years since it was implemented, and relative to the PM policy enacted further back in 2008.

However, the area under regeneration can improve significantly in the coming years, with the implementation of restoration projects. Letting areas regenerate naturally is one of the cheapest options for the landowner to recover areas with low investments in fences whenever necessary, to avoid cattle. Thus, the accomplishments of this policy implementation should be re-assessed in the near future, and the findings will be very important for the persistence of natural regeneration.

Crops and pasture

The persistent areas occupied by clean pasture and crops suggest different responses to the persistence of natural regeneration, even when controlling for other factors. The marginal effect of livestock significantly adds 4.4 ha (2.1-6.6) ($p<0.01$) of persistent natural regeneration for each additional 100 ha of persistent clean pasture. In contrast, the persistent agriculture has no significant effect ($p=0.179$) on the persistence of natural regeneration. In both cases, these results were as predicted. It is noteworthy that the extension of persistent agriculture is currently 10 times smaller than clean pasture, with areas of 15,424km2 and 143,264km2, respectively.

As discussed in Chapter 5, crops are profitable and well established production systems. Therefore, it has a low dynamic of losses for other land uses, for instance, less than 1% (150km2) of the total crop area were abandoned, and classified as secondary vegetation. In contrast, the gains were substantial, around 150% (18,354km2 to 45,050km2) in the period, mostly from pastures, 62% and 25% from pristine forests, but only 1,884km2 (6.6%) originated in natural regeneration (Table 2.9) results support the findings of the model of a positive and significant effect of pastures, but no significant effect of crops on the persistence of natural regeneration.

In summary, as reported elsewhere, in the Amazon, extensive ranching still produces low-yield products, with low technological development and susceptible to land speculation (Hecht, 1993b; Bowman et al., 2012; Garrett et al., 2017). For this reason they remain a low investment and added value lands (Nepstad et al., 2009; Bowman et al., 2012). By contrast, agriculture, especially soy, has shown a substantive land value added on frontier expansion areas (Kaimowitz and Angelsen, 1998; Cattaneo, 2001; Angelsen and DeFries, 2010). This may also help to explain the persistence of agricultural lands and the strong clustering in the central area of Mato Grosso, as a consolidated frontier with high productivity yields and increasing intensification with double-crops (Spera et al., 2014). Angelsen and DeFries (2010) elaborated on Von Thünen's land rent framework and suggested that more recent agriculture is spatially delinked to deforestation, in line with Macedo et al. (2012). As agriculture is consolidated in closer and more accessible areas with higher rent costs, it has displaced pastures lands, as we found here, in line with other studies (Macedo et al., 2012; Meyfroidt et al., 2014), pushing cattle to move to more distant areas. A classical representation of Von Thünen model, where cattle is further away from the centre.

Roads and highways

Counterintuitively, roads suggest a significant positive increase of 4.9 ha (2.6-7.3) ($p<0.01$) of persistent natural regeneration for every km of road added to the network. Roads mean accessibility in the vast Amazon forest, whether for good or bad. Therefore, unpaved roads are another key component of deforestation that have spread at the Amazon frontiers. These are mostly unofficial, and are open daily under the canopy of native vegetation, to access new areas to be explored and ultimately deforested. This is sometimes legal, but mostly not, as partially speculation and land grabbing (Hecht, 1993a; Aldrich et al., 2006; Araujo et al., 2009; Bowman et al., 2012; Rudel and Meyfroidt, 2014). Nevertheless, the remote sensing monitoring system is capable of detecting it together with selective logging and deforested areas through habitat clearance. In combination with the environmental agency operations, it can be disrupted at its early stages. Leaving behind some deforested areas that, if not disturbed again, will start a forest recovery process. In addition, as discussed in Chapter 4, the poor condition of roads and poor access can cause higher transport costs, making activities impossible in certain areas. Consequently, this could lead to higher rates of abandonment and an increase in persistence of natural regeneration.

In-migrants

It was no surprise that the percentage of non-resident population (in-migrants) had a significant negative effect on the persistence of natural regeneration, 1% increase in non-residents goes along with a decrease of 80 ha (44-117) ($p<0.01$) of persistent natural regeneration. In line with (Perz and Skole, 2003b p38) "municipalities receiving more rural migrants should have less secondary growth."

The Amazon region has a long history of waves of occupation and deforestation (Moran, 1981; Moran, 1993; Perz and Skole, 2003b; Garcia et al., 2007; Brondizio and Moran, 2008; Brondizio and Moran, 2012; VanWey et al., 2012). The most recent started in the late sixties of the last century, encouraging people with no land in other regions of Brazil, to move to lands with no people in the Amazon. The perception of this wave of occupation is still alive nowadays: occupy to produce and live on your own legal piece of land. Since its inception in the early 1960s, this social inclusion policy targeted the poorest, and has settled more than 1.3M families in 88M ha, in settlements provided land for landless families (Moran, 1981; Fearnside, 2001; van de Steeg et al., 2006; Merry et al., 2008; Leite et al., 2011; INCRA, 2018).

Inevitably, on arrival, these families had to clear forests, at least, to start subsistence agriculture. Thus, they have to clear forested areas or secondary vegetation areas. The latter is considerably easier to clear and will have a negative impact on the natural regeneration persistence as suggested by our findings described above. More recently, some settlements adopted more sustainable concepts (Alencar et al., 2016; Assunção and Rocha, 2016). As reported elsewhere, settlements have heterogeneous effects on deforestation and natural regeneration (Ludewigs et al., 2009). People that moved into the Amazon may not be adequately aware of climatic conditions, and especially rain and temperature, may affect their crops and pastures. In turn, this led to a premature abandonment of the land through not knowing how to deal with climatic conditions, in the absence of technical support from the government or simply because they were settled in areas with very low capacity for agricultural activity.

However, this is just part of the reason why foreigners come to the Amazon rainforest. Others result from the low price of lands, and weak control of the law. Others may be fugitives convicted of mining precious minerals like diamonds and gold. Others seek the possibility of developing or expanding commodity production like, soy, maize and beef, and not necessarily in compliance with the law. Furthermore, it is easier, cheaper and less risky to clean an area under regeneration against a forested area of natural habitat, as explained earlier in this section. It is less risky, simply because the federal government do not monitor the secondary vegetation[38] as it does with forests. Indeed, it is only partially monitored, fined and embargoed areas have a follow-up to avoid recurrence. This may be a blind spot in the government strategy that is being exploited by offenders.

Non-forest areas

It was very important to control for the non-forest areas, such as Cerrado formations, once it is not observed by the deforestation and land use change monitoring systems. Otherwise, some important municipalities with high shares of non-forest areas could bias the effects of persistence on natural regeneration. Therefore, a 1% increase in non-forest area reduce 65 km2 (46-84) ($p<0.01$) of natural regeneration. So, as the non-forest share increases, the possibility of any land use change towards natural regeneration is smaller. Hitherto, it is according to what was expected, as only forested areas were mapped for land use change and deforestation.

Results in previous studies from the early 2000's suggested that there was an associated increase in secondary forests with the rise of deforestation (Perz and Skole, 2003a; Neeff et al., 2006). By contrast, my results suggested a different direction. As deforestation declined significantly between 2004 and 2014, natural regeneration has increased from 100,674km2 to 173,387km2 (Almeida et al., 2016). Furthermore, the percentage of accumulated deforestation occupied by natural regeneration also increased from 16.4% in 2004 to 22.8% in 2014. From 2012 to 2014 the percentage of natural regeneration remained constant whilst deforestation was stable at around 5,100 km2.

This rise in the area of secondary vegetation, as a co-benefit of deterring deforestation, is probably due to more frequent law enforcement operations. In the long term, however, we may experience a different trend, if we consider that the NGO's pledge: "zero new deforestations" (Azevedo et al., 2015; Moutinho et al., 2016) is successfully implemented/enforced. The immediate and obvious

[38] Only very recent, in 2018, Ibama started to monitor secondary vegetation.

target of the offenders will be secondary vegetation. But not only for them, but also some genuine landowners in search of opportunities for expanding their activities. This may lead to a reduction of areas under recovery and jeopardize the Brazilian restoration commitments in the Paris Agreement. The consequences could be a significant reduction in carbon sinks and loss of connectivity among landscapes intended for biodiversity.

Moreover, the results of this study suggest that environmental police are capable of halting drivers of disturbance, in line with the findings of Melo et al. (2013). Indeed, this is one of the most important steps to initiate restoration in a landscape. It can be an important ally in the achievement of the 12M ha of restoration goals supported by the Brazilian Nationally Determined Contribution (NDC) to the Paris Agreement by 2030.

Indeed, passive regeneration in the Amazon is a feasible option for a low cost, large-scale restoration that should focus on carbon and biodiversity. To start such an ambitious large-scale restoration, a diagnosis would be very important. Therefore, these analysis must assess the most appropriate areas for natural regeneration, considering the ecosystem resilience, land use history and landscape context of the local area (Hobbs and Harris, 2001; Hobbs, 2005; Cramer et al., 2007; Holl and Aide, 2011; Morrison and Lindell, 2011). Hence, passive restoration areas will be: identified; classified whether passive or active; and, prioritized. At the same time, the levels of intervention for active restoration should be publicized, in order to minimize the high costs of active restoration in degraded lands and to maximize natural regeneration. A reasonable proportion of the necessary restoration can be achieved by natural regeneration, as Melo et al. (2013) suggest for the Atlantic Forest biome, where around 50% of landscapes have qualified for passive restoration at low cost.

In turn, in the Amazon region has been less intensively used as areas for cropping and pasture. Therefore, the Amazon should be the priority for passive restoration. Furthermore, Nunes et al. (2015) suggests that the focus should be on large properties which account for a high proportion of forest debts. The selection would also benefit from the 'inclusion of other environmental services like water, preventing soil erosion and connectivity of functional landscapes for biodiversity conservation' (Latawiec et al., 2015 p213).

Such initiatives must have a robust governance structure, and a central coordination unit is imperative, to regulate, monitor, provide guidance, high standards for training for regional and decentralized implementation groups, and initiatives. Restoration projects must consider full ecological recovery as an achievement/final target. It has to be carbon and biodiversity focused. Some large scale restoration projects are criticized for not considering an ecological recovery approach. In addition, restoration has to incorporate the provision of ecosystem services and socioeconomic development of rural areas.

Some active restoration has started to take place in the Amazon, hand-in-hand with CAR implementation. Landowners have been restoring their legal reserves and permanent protection areas, to be in compliance with the new Forest Code. All this will require the support of a wide range of stakeholders and sources of funds including: local government; state government; federal government; local and international NGOs; the Amazon Fund initiative; Global Environment Facility (GEF); and the German and Norwegian governments.

Restoration is a long term process (Martin et al., 2013) and embraces some associated risks. For example, Zahawi et al. (2014) pointed out that the speed of passive restoration can be seen as a failed project that is not being taken seriously by landowners, unless they are forced to. Their second point focusses on the costs. Even passive restoration has to bear some costs for materials, fence construction along with repairs, and labour expenses associated with fires and regular visits. The combination of these two factors, along with weak environmental law enforcement, brings risks to the persistence of natural restoration.

So, if restoration is dependent on the landowners' discretion, economic solutions must be budgeted (Rodrigues et al., 2009b; Rodrigues et al., 2011; Latawiec et al., 2015). However, landowners usually do not have the capital and expect an economic return from their investment. Motivation will be crucial to encourage participation and when it could be translated into a different economic return. Vieira et al. (2014 p1749) point out that "it is vital that second-growth forests are ultimately recognized as being a benefit, rather than an impediment".

6.4.3 Study limitations

This study was limited to a 10-year period, although the fallow period in the Amazon can last from 3 to 30 years depending on several factors, especially the technology used in cattle ranching (Fearnside, 1996; Neeff et al., 2006; Laue and Arima, 2014). Therefore, a portion of the persistent natural regeneration might only be in a fallow period, while waiting to be used again in the next fallow period. A longer period of evaluation is necessary, going back to the 1990 and 2000's, and continuing forwards to 2018, with high resolution mapping. It would certainly provide precious information on land use changes and persistent areas of natural regeneration to gain a more robust understanding of its drivers and effects.

The study exposed some of the triggers for using natural regeneration areas. First, it could be the property fallow cycle itself. Second, the extensive presence of the law enforcement controlling deforestation of natural habitats, and the much weaker control of the natural regeneration areas. Third, changes in government environmental priorities and budget constraints could cause a relaxation of law enforcement. Fourth, the pressure from the market, retailers and NGOs' for a clean supply chain with no natural habitat conversion. The most prominent example is the Brazilian Amazon Soy Moratorium. Fifth, an accelerating rate of economic momentum.

It was beyond the scope of this study to evaluate the vegetation successional stage of the persistent areas of natural regeneration. In other words, an area that has been there for ten years does not necessarily represent a 10-year old secondary vegetation. Human interferences like the incidence and recurrence of fires, history of land use, through time, intensity and isolation, can delay the process of natural regeneration (Nepstad et al., 1996; Walker et al., 2002; Perz, 2003; Perz and Skole, 2003b; Rodrigues et al., 2009b; Rodrigues et al., 2011; Melo et al., 2013; Latawiec et al., 2015). Here, the investigation was limited to the year of deforestation and property size of the area with persistent natural regeneration (Table 6.3 and Table 6.4).

Further research is needed to investigate the passive regeneration in more detail, in terms of carbon accumulation and landscape connectivity for biodiversity. It is well known that secondary vegetation plays an important role in providing structural and functional connectivity in the landscape.

6.5 Conclusions

In applying the best statistical approach to the case, this study found that fines play a very important role in the amount and persistence of natural regeneration presence in the landscape. However, I did not find any leakage effect, which suggests that fines in a municipality do not impact the persistence of secondary vegetation of its neighbours'.

Hence, environmental law enforcement is significant for the persistence of natural regeneration in the Amazon and elsewhere. So far, the literature points to socioeconomic reasons as the most frequent cause of land abandonment (Perz, 2000; Perz and Skole, 2003b; Shoo et al., 2013; Laue and Arima, 2014). It is more difficult to find cases of abandonment based on command and control through environmental police operations, as in this study. One exception is the work of Rodrigues et al. (2011) that suggests that abandonment of large properties in the Atlantic Forest in Sao Paulo state of Brazil was due to law enforcement.

Almost a third of the Brazilian NDC restoration commitment could come from the natural regeneration taking place in the Amazon as reported here (41,426 km2). An optimistic perspective shows that 38,251 km2 of persistent natural regeneration of six years old (2008-2014) can be added. Since, this consistent trend continues, over 2/3 of the Brazilian 2030 restoration target could be covered by passive or low cost active restoration. As presented in this study environmental law enforcement could play an important role in restoration goals.

Even though this chapter suggests that law enforcement operations on the ground could have a positive impact on the persistence of natural regeneration, protecting primary forests is still the best option to mitigate climate change. 'Primary forests tend to be more resilient to climate change and other human-induced environmental changes than secondary forests and plantations' (Thompson et al., 2009) (Chapter 11 of the 5th IPCC report, p846).

7 Final remarks and conclusions

I conclude where I started, with the conviction that it is possible to balance conservation and production. I have shed light on some pieces in this complex puzzle and shown how they can influence this balance for the Brazilian Amazon. Consequently, the results of this thesis are encouraging and point to the strong potential impact of law enforcement on increasing the persistence of natural regeneration, reducing forest loss, and reshaping the land use system towards intensification in the Brazilian Amazon. Indeed, environmental law enforcement has been very effective in the Amazon context.

Throughout the study period from 2004-2014, Brazil has shown that a strong combination of policies and massive collaboration among all sectors, whether governments, civil society, producers, traders, and retailers, nationally and internationally, working on supply and demand sides, can lead to a low carbon economy. As the results of this thesis have shown, the dynamics of land-use change in regions like the Brazilian Amazon are complex and require sophisticated arrangements to deliver the desired outcomes.

Consequently, it is vital to encourage and promote an evolution in governance. This should combine the approaches of soft and hard law, as instruments aimed at reaching different actors, acting in complementary ways in pursuit of the same goal: to achieve a balance between conservation and production. However, it is also clear that this nexus is still unstable in many areas, and any political and/or policy perturbation may cause big losses and quickly reverse previously solid advances. Therefore, the challenge ahead is to make this balance consistent, stable, and less vulnerable to perturbations. Hence, a better understanding is needed of the adequate combination and sequencing of policy mixes that will help improve future design, implementation and performance.

High levels of political will are required by governments to halt tropical deforestation. This need for strong political will is at the core of any initiative to change the course of forest loss, of feeding a hungry planet and promoting the necessary and desirable development of a low carbon economy over the entire globe. The transformation of predatory activities in tropical forests into a sustainable model remains a constant challenge and requires coordinated actions in the three fundamental pillars of sustainable development:

- environmental,
- social and
- economic.

In this context there is no room for radicalism within any of the pillars. Instead, an incessant search is required to achieve a balance between these three forces which will determine the development that is needed for the Amazon, and the planet more generally. Furthermore, environmental issues are at the heart of a new global low carbon economy.

Having said that, governance remains the key factor in land management (Roitman et al., 2018). Governance has only one possible path in the Amazon, through long term collaboration among different stakeholders and strong commitment, a path that certainly is not easy. Governments at all levels, whether federal, state and municipal, civil society, producers, traders, retailers and consumers must row together, and in the same direction, if humankind really means to reverse deforestation and mitigate climate change. Furthermore, international collaboration must be part of the equation, through international mechanisms already established as REDD+ and the Green Climate Fund under UNFCCC. Also, through institutional arrangements like the Pilot Program for Tropical Forests Protection - PPG7, a long-term initiative that left a great legacy, with strong support and collaboration among the G7 countries, international non-governmental organizations, Brazilian society and government.

Combating tropical deforestation is a gigantic global challenge that needs to be tackled locally and on a daily basis. Simple and understandable messages are very important to help this enormous challenge become much more tangible when building initiatives and actions in local and regional arrangements, with wide participation. All possible local and regional arrangements must be encouraged and pursued with an inclusive and participatory governance framework to be successful. As suggested by Patuelli et al. (2012 p.3) "policy makers who understand the specific characteristics of a region…are able to tackle problems more effectively and to anticipate more accurately the necessary responses". This approach also increases the sense of ownership and belonging to the resulting achievements. This was the case for the municipalities of Paragominas/PA and Alta Floresta/MT that entered the list of priority municipalities yet managed to reverse the alarming rates of deforestation, and leave the list a few years later. This change was achieved through broad mobilization of the local municipal government, in collaboration with the federal government, state government, organized civil society, local producers associations, independent producers, research institutions, and environmental and social non-governmental organizations.

The results of this thesis also point to the potential of environmental law enforcement as a catalyst for reshaping Amazon land use. Conversion of forest to alternative uses has reduced, and thereby increased the exchange of land on cleared areas, and increased natural regeneration. Moreover, there has been an increase in the tax collected in priority municipalities with the largest presence of enforcement, suggesting a possible migration to legal activities, an important sign in combating illegal activities and tax evasion. Therefore, policy approaches should consider a sustainable landscape perspective, a development model that looks at the different perspectives of actors who make up the landscape, so that policies are specific enough to seek appropriate solutions in every situation.

In this context, Environmental Economic Zoning (EEZ) is a strategic public policy for landscape planning and regional development. Based on spatial information, EEZ should guide public policies to achieve optimal land use in order to maximize the balance and benefits of conservation and development. Thus, any changes should prioritize incentives to adopt a low carbon agriculture, with semi-intensification of the cattle herd, or even a reduction or exchange to encourage alternative sources of protein with lower emissions, consistent with the forest conservation policy. In addition, highly suitable lands for agricultural should be prioritized for this purpose. However, it is a huge challenge for governments to fully implement an EEZ, and land tenure and environmental law enforcement will be central to the success of a landscape initiative approach.

Governance and landscape planning raise two key issues in attempting to move out of the vicious cycle of forest loss into the virtuous cycle of ecosystem restoration and sustainable development of the largest continuous rainforest on the planet, before the Amazon reaches the tipping point of no return (Lovejoy and Nobre, 2018).

The lack of clarity over land ownership remains one of the main bottlenecks to resolve in the Amazon. Land tenure and property rights still remain a considerable threat to control deforestation. So, the success of combating deforestation necessarily involves solving this issues and the adequate designation of undesignated public lands, a constant target of land grabbers and offenders. These areas account for significant portions of recent deforestation (see Chapters 2 and 4). Therefore, it is imperative that governments seek faster solutions to ensure land security. The Brazilian government took an important step to accelerate land designation by creating an inter-ministerial working group in 2012. So far, 47.8M out of 60M ha of federal lands have already been designated: 34.7M for land tenure regularization, 1.5M ha with land titles emitted, 7.5M ha for new protected areas, 0.1M ha for settlements, 2,500 ha for Indigenous lands and 4M ha had been defined before the working group started. Another 10.6M ha are under evaluation, 1.8M ha are pending for consultation, and finally 1.6M ha has yet to be designated. Despite the encouraging results, the work has not yet been completed, and it is still insufficient to solve the problem.

Certainly, land rights are a key component of deforestation control and land use governance, requiring further investigation. Here I have only explored the tip of the iceberg of this complex puzzle of the Amazon land use system. So, when solved, or at least when showing strong political will to overcome the problem, will facilitate public and private partnerships, and the investments for a sustainable intensification of agriculture, consequently, sparing lands for conservation. Moreover, if combined with the appropriate economic incentives, it can significantly boost sustainable investments to reach the scale the Amazon demands.

In parallel, law enforcement has made a considerable contribution in the field. However, law enforcement has faced some administrative limitations that need to be overcome to renew the challenges, and not to let the idea spread among offenders that they can act with impunity (see Chapter 4). In addition, the recurrent forgiveness of debt offered for farmers' loans also does not favor an increase in efficiency and in the quality of Brazilian agriculture, which may be consigned as areas of low productivity in perpetuity.

Government incentives need to be aligned with the needs of a low-carbon economy. A considerable slice of the agricultural sector in Brazil is looking into the 21st century and clearly understands that the sustainability of Brazilian agriculture needs to be synchronized with the conservation of natural environments and the reduction of GHG emissions. The overall aim would be to seek for more efficiency in production, under the penalty of having to reduce productivity and eventually restrict Brazilian commodities in important international markets. Unlike groups that remain in the practice of past-century agriculture, the market will certainly shrink, while information on the availability of supply chain and transparency grows exponentially. Hence, provided with information for their decision-making process, farmers can have orders cancelled by international partners, as seen in some recent initiatives with the escalation of deforestation and fire in the Amazon. For example, some companies have stopped importing Brazilian leather, and soybeans to feed salmon farms. So, the incentives for a modern and more sustainable agricultural sector must outperform and be hegemonic in the short-term for the proper confrontation of climate change and the development of a low-carbon economy. Hence, Brazil will become one of the global leaders in agricultural commodities for human and animal populations.

Moreover, the globalized economy is showing a considerable and growing influence on deforestation, as economic improvements and growing urbanization in certain countries pushes and/or triggers agricultural production in distant regions (McAlpine et al., 2009; DeFries et al., 2010; Arima et al., 2011; Fearnside et al., 2013; Meyfroidt et al., 2013; Fearnside and Figueiredo, 2015).

For instance, the food security safeguards of a nation like China require the internal production of up to 85% of their basic food supply needs. This will have important consequences in other regions to supply the increasing demands of the economic growth (GDP) in China, where people now consume more meat, especially pork. As a consequence, the gap in demand for cereals needs to be plugged to feed the pork herd in distant countries like Brazil. China responds by sourcing the largest and growing share of Brazilian exports up to 19% of total, and growing at astonishing annual rates of 40.4% from 2000-2008 (Fearnside and Figueiredo, 2015). There is a clear need for improvements in Brazil-China trade agreements and commitments, in order to guarantee a clean and deforestation-free supply-chain for Chinese industry. This is certainly not an easy task as China imports commodities from many different nations worldwide, with considerable variations on environmental legislation requirements. However, both countries have proven to be great leaders and direct influencers in climate negotiations. Therefore they must join efforts to seek an agreement aiming at low carbon agriculture and lead the necessary transformation.

Another example is the very wealthy market of Europe, which has decreased its agricultural areas at the expense of importing products from other regions of the planet, and displacing their contribution to global forest loss to other nations (Mills Busa, 2013), thereby sustaining internal consumption, while shaping regrowth rates of forests within their borders, and moving to the final stages of the forest transition. Consequently, tropical countries like Brazil and Indonesia have absorbed the growing global demands for key agricultural products like soy, meat and palm oil (Meyfroidt et al., 2013).

Therefore, transparency and traceability of the supply chain of agricultural commodities in the global market must be pursued tirelessly as a benchmark. As on the demand side, consumers are increasingly demanding this attitude from their supermarkets and retailers, considered a key factor that can contribute to eliminating deforestation. However, there is still a long way to go, as reported in 2016 by Lambin et al. (2018). Only one in four of Consumer Goods Forum member companies had put measures in place to ensure compliance in their business processes or suppliers. Nevertheless, the private sector and banks have an important complementary role to play in law enforcement on the one hand, and consumers on the other hand.

Last but not least, this study has shed light on the impact of law enforcement on natural regeneration. Indeed, this is the century for ecosystem restoration, the new mantra of the century, as emphasized by T. Lovejoy (*personal comm.*).

Deforestation will not end by working only in the Amazon. It is necessary go beyond the biome and national borders, to engage with neighbouring countries, the buyers and consumers of all products and commodities coming from the Amazon, working on both supply and demand sides of the equation.

In the broader perspective, combating illegal activities will always be an endless and tough task in which some battles are won, using all the policy and support that is in place. However, the war will still be there challenging those who are involved, every single day.

8 References

ABIOVE 2017. Soy Moratorium Monitoring annual report. . Sao Paulo: Associação Brasileira das Industrias de Óleos Vegetais. accessed 20Sep2018.

AGROSATELITE 2016. 8o Relatorio da Moratoria da Soja. Sao Paulo: Abiove.

AGUIAR, A. P. D., CÂMARA, G. & ESCADA, M. I. S. 2007. Spatial statistical analysis of land-use determinants in the Brazilian Amazonia: Exploring intra-regional heterogeneity. *Ecological Modelling,* 209: 169-188.

ALDRICH, S., WALKER, R., SIMMONS, C., CALDAS, M. & PERZ, S. 2012. Contentious Land Change in the Amazon's Arc of Deforestation. *Annals of the Association of American Geographers,* 102: 103-128.

ALDRICH, S. P., WALKER, R. T., ARIMA, E. Y., CALDAS, M. M., BROWDER, J. O. & PERZ, S. 2006. Land-Cover and Land-Use Change in the Brazilian Amazon: Smallholders, Ranchers, and Frontier Stratification. *Economic Geography,* 82: 265-288.

ALENCAR, A., NEPSTAD, D., MCGRATH, D. & MOUTINHO, P. 2004. Desmatamento na Amazônia: indo além da "emergência crônica". Belém: IPAM.

ALENCAR, A., PEREIRA, C. A., CASTRO, I., CARDOSO, A., SOUZA, L., COSTA, R., BENTES, A. J., STELLA, O., AZEVEDO, A., GOMES, J. & NOVAES, R. 2016. Desmatamento nos Assentamentos da Amazônia: Histórico, Tendências e Oportunidades. *In:* IPAM (ed.). Brasilia: IPAM.

ALIX-GARCIA, J. & GIBBS, H. K. 2017. Forest conservation effects of Brazil's zero deforestation cattle agreements undermined by leakage. *Global Environmental Change,* 47: 201-217.

ALIX-GARCIA, J., RAUSCH, L., L'ROE, J., GIBBS, H. K. & MUNGER, J. 2017. Avoided deforestation linked to environmental registration in the Brazilian Amazon. *In:* DEPARTMENT OF AGRICULTURAL AND APPLIED ECONOMICS, U. O. W.-M. (ed.).

ALMEIDA, C. A. D., COUTINHO, A. C., ESQUERDO, J. C. D. M., ADAMI, M., VENTURIERI, A., DINIZ, C. G., DESSAY, N., DURIEUX, L. & GOMES, A. R. 2016. High spatial resolution land use and land cover mapping of the Brazilian Legal Amazon in 2008 using Landsat-5/TM and MODIS data. *Acta Amazonica,* 46: 291-302.

ALSTON, L. J., LIBECAP, G. D. & SCHNEIDER, R. 1995. Property Rights and the Preconditions for Markets: The Case of the Amazon Frontier. *Journal of Institutional and Theoretical Economics (JITE) / Zeitschrift für die gesamte Staatswissenschaft,* 151: 89-107.

ANDRÉN, H. 1994. Effect of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *Oikos,* 71: 355-366.

ANGELSEN, A. & DEFRIES, R. S. 2010. Policies for reduced deforestation and their impact on agricultural production. *Proceedings of the National Academy of Sciences of the United States of America,* 107: 19639-19644.

ANGELSEN, A. & KAIMOWITZ, D. 1999. Rethinking The Causes Of Deforestation. *World Bank Research Observer,* 14: 73-98.

ARAUJO, C., BONJEAN, C. A., COMBES, J.-L., COMBES MOTEL, P. & REIS, E. J. 2009. Property rights and deforestation in the Brazilian Amazon. *Ecological Economics,* 68: 2461-2468.

ARAÚJO, M. B., THUILLER, W. & PEARSON, R. G. 2006. Climate warming and the decline of amphibians and reptiles in Europe. *Journal of Biogeography,* 33: 1712-1728.

ARIMA, E. Y. 2016. A Spatial Probit Econometric Model of Land Change: The Case of Infrastructure Development in Western Amazonia, Peru: e0152058. *PLoS One,* 11.

ARIMA, E. Y., BARRETO, P., ARAUJO, E. & SOARES, B. 2014. Public policies can reduce tropical deforestation: Lessons and challenges from Brazil. *LAND USE POLICY,* 41: 465-473.

ARIMA, E. Y., RICHARDS, P., WALKER, R. & CALDAS, M. M. 2011. Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environmental Research Letters,* 6.

ARIMA, E. Y., WALKER, R. T., PERZ, S. & SOUZA, C. 2015. Explaining the fragmentation in the Brazilian Amazonian forest. *Journal of Land Use Science*: 1-21.

ARIMA, E. Y., WALKER, R. T., SALES, M., SOUZA JR, C. & PERZ, S. G. 2008. The fragmentation of space in the Amazon basin: Emergent road networks. *Photogrammetric Engineering and Remote Sensing,* 74: 699-709.

ASNER, G. P., RUDEL, T. K., AIDE, T. M., DEFRIES, R. & EMERSON, R. 2009. A Contemporary Assessment of Change in Humid Tropical Forests Una Evaluación Contemporánea del Cambio en Bosques Tropicales Húmedos. *Conservation Biology,* 23: 1386-1395.

ASSUNÇÃO, J., GANDOUR, C., PESSOA, P. & ROCHA, R. 2017. Property-level assessment of change in forest clearing patterns: The need for tailoring policy in the Amazon. *Land Use Policy,* 66: 18-27.

ASSUNÇÃO, J., GANDOUR, C. & ROCHA, R. 2013. DETERring Deforestation in the Brazilian Amazon: Environmental Monitoring and Law Enforcement. Climate Policy Initiative RJ.

ASSUNÇÃO, J., GANDOUR, C. & ROCHA, R. 2015. Deforestation slowdown in the Brazilian Amazon: prices or policies? *ENVIRONMENT AND DEVELOPMENT ECONOMICS,* 20: 697-722.

ASSUNÇÃO, J., GANDOUR, C., ROCHA, R. & ROCHA, R. 2016. The Effect of Rural Credit on Deforestation: Evidence from the Brazilian Amazon. Rio de Janeiro: Nucleo de avaliação de políticas publicas - PUC-Rio. Climate Policy Initiative.

ASSUNÇÃO, J. & ROCHA, R. 2014. Getting Greener by Going Black: The Priority Municipalities in Brazil. CPI Rio Reports.

ASSUNÇÃO, J. & ROCHA, R. 2016. Rural Settlements and Deforestation in the Amazon. RJ: Puc-Rio.

AZEVEDO-RAMOS, C. & MOUTINHO, P. 2018. No man's land in the Brazilian Amazon: Could undesignated public forests slow Amazon deforestation? *Land use policy. Volume 73*.

AZEVEDO, A. A., RAJAO, R., COSTA, M. A., STABILE, M. C. C., MACEDO, M. N., DOS REIS, T. N. P., ALENCAR, A., SOARES-FILHO, B. S. & PACHECO, R. 2017. Limits of Brazil's Forest Code as a means to end illegal deforestation. *Proc Natl Acad Sci U S A*.

AZEVEDO, A. A., STABILE, M. C. C. & REIS, T. N. P. 2015. Commodity production in Brazil: Combining zero deforestation and zero illegality. *Elementa: Science of the Anthropocene,* 3: 12.

BACEN 2008. Resolução Nº 3.545 do Banco Central do Brasil - Altera o MCR 2 - 1 para estabelecer exigência de documentação comprobatória de regularidade ambiental e outras condicionantes, para fins de financiamento agropecuário no Bioma Amazônia. . *In:* BRASIL, B. C. D. (ed.). Brasilia: Banco central do Brasil.

BALÉE, W. 1989. The culture of Amazonian forests. *In:* POSEY, D. A. B., W. (ed.) *Resource management in Amazonia: indigenous and flok strategies.* New York: New York Botanical Garden.

BALMFORD, A., GREEN, R. & PHALAN, B. 2012. What conservationists need to know about farming. *Proceedings: Biological Sciences,* 279: 2714-2724.

BALMFORD, A., GREEN, R. E. & SCHARLEMANN, J. P. W. 2005. Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Global Change Biology,* 11: 1594-1605.

BARBIER, E. B., CATTANEO, A., BASHAASHA, B., KRAYBILL, D. S., SOUTHGATE, D. D., COXHEAD, I., ROLA, A., KIM, K., SHIVELY, G. E., ANGELSEN, A., AMACHER, G. S., CROPPER, M., BRAZEE, R. J., WITVLIET, M., PURI, J., GRIFFITHS, C., NELSON, G. C., HARRIS, V., STONE, S. W., KÖHLIN, G. & PARKS, P. J. 2001. Tropical deforestation and land use. *Land economics,* 77: 155-313.

BARRETO, P., PEREIRA R. & ARIMA E. 2008. A pecuária e o desmatamento na Amazônia na era das mudanças climáticas. Belém, PA, Brasil: Imazon.

BARRETTO, A. G. O. P., BERNDES, G., SPAROVEK, G., WIRSENIUS, S., INSTITUTIONEN FÖR ENERGI OCH MILJÖ, F. R., DEPARTMENT OF, E., ENVIRONMENT, P. R. T., CHALMERS UNIVERSITY OF, T. & CHALMERS TEKNISKA, H. 2013. Agricultural intensification in Brazil and its effects on land-use patterns: an analysis of the 1975–2006 period. *Global Change Biology,* 19: 1804-1815.

BATISTELLA, M., ROBESON, S. & MORAN, E. F. 2003. Settlement Design, Forest Fragmentation, andLandscape Change in Rondônia, Amazônia. *Photogrammetric Engineering & Remote Sensing,* 69: 8.

BBC 2013. Rancher convicted over murder of US nun Dorothy Stang *In:* HTTPS://WWW.BBC.CO.UK/NEWS/WORLD-LATIN-AMERICA-24177359 (ed.) *BBC News.* BBC News.
BECHARA, F. C., DICKENS, S. J., FARRER, E. C., LARIOS, L., SPOTSWOOD, E. N., MARIOTTE, P. & SUDING, K. N. 2016. Neotropical rainforest restoration: comparing passive, plantation and nucleation approaches. *Biodiversity and Conservation,* 25: 2021-2034.
BECKER, G. S. 1968. Crime and Punishment: An Economic Approach. *Journal of Political Economy,* 76: 169-217.
BERKES, F. 2004. Rethinking community-based conservation. *Conservation Biology* 18: 621-630.
BERKES, F. 2007. Community-based conservation in a globalized world. *Proceedings of the National Academy of Sciences of the USA* 104: 15188-15193.
BORNER, J., KIS-KATOS, K., HARGRAVE, J. & KONIG, K. 2015a. Post-Crackdown Effectiveness of Field-Based Forest Law Enforcement in the Brazilian Amazon: e0121544. *PLoS ONE,* 10.
BORNER, J., MARINHO, E. & WUNDER, S. 2015b. Mixing Carrots and Sticks to Conserve Forests in the Brazilian Amazon: A Spatial Probabilistic Modeling Approach: e0116846. *PLoS ONE,* 10.
BORNER, J., WUNDER, S., WERTZ-KANOUNNIKOFF, S., HYMAN, G. & NASCIMENTO, N. 2014. Forest law enforcement in the Brazilian Amazon: Costs and income effects. *GLOBAL ENVIRONMENTAL CHANGE-HUMAN AND POLICY DIMENSIONS,* 29: 294-305.
BOUCHER, D., ELIAS P., J., F. & SMITH S. 2014. Deforestation Success Stories: Tropical Nations Where Forest Protection and Reforestation Policies Have Worked. Tropical Forest and Climate Initiative (TFCI) of the Union of Concerned Scientists (UCS).
BOWEN, M. E., MCALPINE, C. A., HOUSE, A. P. N. & SMITH, G. C. 2007. Regrowth forests on abandoned agricultural land: A review of their habitat values for recovering forest fauna. *Biological Conservation,* 140: 273-296.
BOWEN, M. E., MCALPINE, C. A., SEABROOK, L. M., HOUSE, A. P. N. & SMITH, G. C. 2009. The age and amount of regrowth forest in fragmented brigalow landscapes are both important for woodland dependent birds. *Biological Conservation,* 142: 3051-3059.
BOWMAN, M. S., SOARES-FILHO, B. S., MERRY, F. D., NEPSTAD, D. C., RODRIGUES, H. & ALMEIDA, O. T. 2012. Persistence of cattle ranching in the Brazilian Amazon: A spatial analysis of the rationale for beef production. *Land Use Policy,* 29: 558-568.
BRAUN, B. 2015. From critique to experiment? Rethinking political ecology for the Anthropocene *In:* PERREAULT, T. B., GAVIN; MCCARTHY, JAMES (ed.) *Routledge Handbook of Political Ecology.* Book Routledge International Handbooks.
BRAZIL 1953. Federal Act 1806 January 6th 1953. Dispõe sobre o Plano de Valorização Econômica da Amazônia, cria a superintendência da sua execução e dá outras providências. (available at http://www2.camara.leg.br/legin/fed/lei/1950-1959/lei-1806-6-janeiro-1953-367342-publicacaooriginal-1-pl.html - accessed on May 30th 2016).
BRAZIL 1964. Estatuto da Terra. LEI Nº 4.504, DE 30 DE NOVEMBRO DE 1964. *In:* REPÚBLICA, P. D. (ed.). Brasilia.
BRAZIL 1966. Federal Act 5,173, October 27th 1966. Dispõe sobre o Plano de Valorização Econômica da Amazônia (available at http://www.planalto.gov.br/ccivil_03/leis/L5173.htm - accessed on May 30th 2016).
BRAZIL 1988. Constituição da República Federativa do Brasil. Brasília: Senado.
BRAZIL 2004. Plan to prevent and control deforestation in the Amazon. Brasilia-DF: Ministry of the Environment.
BRAZIL 2005. DECRETO Nº 5.334 DE 6 DE JANEIRO DE 2005. Dá nova redação ao art. 21 e revoga o art. 22 do Decreto no 89.817, de 20 de junho de 1984, que estabelece as Instruções Reguladoras das Normas Técnicas da Cartografia Nacional. . *In:* IBGE (ed.). Brasilia: IBGE.
BRAZIL 2007. Presidential Decree 6,321, Dec 21st. Dispõe sobre ações relativas à prevenção, monitoramento e controle de desmatamento no Bioma Amazônia, bem como altera e acresce dispositivos ao Decreto no 3.179, de 21 de setembro de 1999, que dispõe sobre a especificação das sanções aplicáveis às condutas e atividades lesivas ao meio ambiente, e dá

outras providências. *In:* HTTP://WWW.PLANALTO.GOV.BR/CCIVIL_03/_ATO2007-2010/2007/DECRETO/D6321.HTM (ACCESSED ON NOV 25TH (ed.). Brasilia: Brazilian Federal Government.
BRAZIL 2009. Federal Act 12,187. Institui a Política Nacional sobre Mudança do Clima - PNMC e dá outras providências. *In:* CIVIL, C. (ed.). Brasilia: Casa Civil.
BRAZIL 2012a. Federal Act 12,651 25 May 2012. . *http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm (accessed on 02 May 2016.).*
BRAZIL 2012b. Presidential Decree 7,830 - Dispõe sobre o Sistema de Cadastro Ambiental Rural, o Cadastro Ambiental Rural, estabelece normas de caráter geral aos Programas de Regularização Ambiental, de que trata a Lei no 12.651, de 25 de maio de 2012, e dá outras providências. *http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/decreto/D7830.htm (accessed on May 27th, 2016).* Brasilia: Brazilian Federal Government.
BRAZIL 2015. Intended Nationally Determined Contribution (INDC) towards achieving the objective of the UNFCCC. Brasilia: Ministry of the Environment (http://mma.gov.br/images/arquivo/80108/BRAZIL%20iNDC%20english%20FINAL.pdf - accessed on May 30th 2016).
BRAZIL 2018. CAR registry bulletin JAN/2018. *In:* BRAZILIAN FOREST SERVICE, M. O. T. E. (ed.). http://www.florestal.gov.br/numeros-do-car (accessed on February 26th, 2018).
BRAZIL, M. O. S., TECHNOLOGY AND INNOVATION. SECRETARIAT OF POLICIES AND PROGRAMS OF RESEARCH AND DEVELOPMENT. GENERAL COORDINATION OF GLOBAL CLIMATE CHANGE 2016. Third National Communication of Brazil to the United Nations Framework Convention on Climate Change – Executive Summary. *In:* MINISTRY OF SCIENCE, T. A. I. (ed.). Brasília: Ministério da Ciência, Tecnologia e Inovação.
BROCKHAUS, M., ANGELSEN, A., ROMIJN, E., FRIES, D. R. S., HOSONUMA, N., VERCHOT, L., HEROLD, M. & SY, D. V. 2012. An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters,* 7.
BRONDIZIO, E. S. 2006. Agriculture intensification, economic identity, and shared invisibility in Amazonian peasantry: caboclos and colonists in comparative perspectives. *In:* ADAMS, C., MURRIETA, R., NEVES, W. & HARRIS, M. (eds.) *Amazon peasant societies in a changing environment: political ecology, invisibility and modernity in the rain forest.* US: Springer
BRONDIZIO, E. S. & MORAN, E. F. 2008. Human dimensions of climate change: the vulnerability of small farmers in the Amazon. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 363: 1803-1809.
BRONDIZIO, E. S. & MORAN, E. F. 2012. Level-dependent deforestation trajectories in the Brazilian Amazon from 1970 to 2001. *Population and Environment,* 34: 69-85.
BROWN, S. & ZARIN, D. 2013. What Does Zero Deforestation Mean? *SCIENCE,* 342: 805-807.
BRYANT, R. L. 1992. POLITICAL ECOLOGY - AN EMERGING RESEARCH AGENDA IN THIRD-WORLD STUDIES. *Political Geography,* 11: 12-36.
BRYANT, R. L. 1999. A Political Ecology for Developing Countries? *Zeitschrift für Wirtschaftsgeographie.*
BRYANT, R. L. & BAILEY, S. 1997. Third World political ecology. London: Routledge.
BURKEY, T. V. 1989. Extinction in nature reserves: the effect of fragmentation and the importance of migration between reserve fragments. *Oikos* 55: 75-81.
BURKEY, T. V. 1995. Extinction rates in archipelagoes: implications for population in fragmented habitats. *Conservation Biology* 9: 527-541.
CABEZA, M., ARPONEN, A., JÄÄTTELÄ, L., KUJALA, H., VAN TEEFFELEN & A., H., I. 2010. Conservation planning with insects at three different spatial scales. *Ecography,* 33: 10.
CALADINO, D., WEHRMANN, M. & KOBLITZ, R. 2012. Contribuição dos assentamentos rurais no desmatamento da Amazônia: um olhar sobre o Estado do Pará. . *Desenvolvimento e Meio ambiente,* 26: 12.

CAMARA, G., VALERIANO, D. M. & VIANEI, J. 2006. Metodologia para o Cálculo da Taxa Anual de Desmatamento na Amazônia Legal *In:* INPE (ed.).

CATTANEO, A. 2001. A General Equilibrium Analysis of Technology, Migration, and Deforestation in the Brazilian Amazon". *In:* ANGELSEN, A. & KAIMOWITZ, D. (eds.) *Agricultural Technologies and Tropical Deforestation.* Wallingford: CABI Publishing.

CAVIGLIA-HARRIS, J. L. 2018. Agricultural innovation and climate change policy in the Brazilian Amazon: Intensification practices and the derived demand for pasture. *Journal of Environmental Economics and Management,* 90: 232-248.

CHAZDON, R. L., BRANCALION, P. H. S., LAMB, D., LAESTADIUS, L., CALMON, M. & KUMAR, C. 2017. A Policy-Driven Knowledge Agenda for Global Forest and Landscape Restoration. *Conservation Letters,* 10: 125-132.

CHILD, B. 2004. *Parks in transition,* London (United Kingdom), Earthscan, IUCN Publication.

CHOMITZ, K. M. & THOMAS, T. S. 2003. Determinants of Land Use in Amazonia: A Fine-Scale Spatial Analysis. *American Journal of Agricultural Economics,* 85: 1016-1028.

CIRNE, P. & RODRIGUES, L. V. 2018. Índio quer soja: Etnia busca apoio dos ruralistas do Congresso para manter lavouras em Mato Grosso - https://www.uol/noticias/especiais/indio-quer-soja.htm#indio-quer-soja?cmpid=copiaecola. *UOL Noticias*, 03Dec2018.

CISNEROS, E., ZHOU, S. L. & BÖRNER, J. 2015. Naming and Shaming for Conservation: Evidence from the Brazilian Amazon. *PloS one,* 10: e0136402.

CONAB 2017. A produtividade da soja: análise e perspectivas. *In:* ABASTECIMENTO, C. N. D. (ed.) *Compêndio de Estudos Conab.* Brasilia: Companhia Nacional de Abastecimento.

CRAMER, V. A., HOBBS, R. J. & SOCIETY FOR ECOLOGICAL RESTORATION, I. 2007. *Old fields : dynamics and restoration of abandoned farmland / edited by Viki A. Cramer and Richard J. Hobbs,* Washington ; London, Washington ; London : Island Press, 2007.

D'ANTONA, A., VANWEY, L. & LUDEWIGS, T. 2011. Polarization in the land distribution, land use and land cover change in the Amazon. *Acta amazonica,* 41: 223-232.

D'ANTONA, Á. O., VANWEY, L. K. & HAYASHI, C. M. 2006. Property Size and Land Cover Change in the Brazilian Amazon. *Population and Environment,* 27: 373-396.

DALE, V. H., PEARSON S.M., OFFERMAN H.L. & O'NEILL R.V. 1994. . Relating patterns of landuse change to faunal biodiversity in the Central Amazon. *Conservation Biology,* 8: 1027-1036.

DALLA-NORA, E. L., DE AGUIAR, A. P. D., LAPOLA, D. M. & WOLTJER, G. 2014. Why have land use change models for the Amazon failed to capture the amount of deforestation over the last decade? *LAND USE POLICY,* 39: 403-411.

DAVIDSON, E. A., DE ARAUJO, A. C., ARTAXO, P., BALCH, J. K., BROWN, I. F., BUSTAMANTE, M. M. C., COE, M. T., DEFRIES, R. S., KELLER, M., LONGO, M., MUNGER, J. W., SCHROEDER, W., SOARES-FILHO, B. S., SOUZA, C. M., JR. & WOFSY, S. C. 2012. The Amazon basin in transition. *Nature,* 481: 321.

DE SOUZA, R. A. & DE MARCO, P. 2015. The Red Queen race in Brazilian Amazon deforestation: the necessity of a sustainable economy to zero deforestation. *Natureza & Conservação,* 13: 190-192.

DE SOUZA, R. A., MIZIARA, F. & DE MARCO JUNIOR, P. 2013. Spatial variation of deforestation rates in the Brazilian Amazon: A complex theater for agrarian technology, agrarian structure and governance by surveillance. *Land Use Policy,* 30: 915-924.

DEFRIES, R. & ROSENZWEIG, C. 2010. Toward a whole-landscape approach for sustainable land use in the tropics. *Proc. Natl. Acad. Sci. U.S.A. ,* 107: 6.

DEFRIES, R. S., RUDEL, T., URIARTE, M. & HANSEN, M. 2010. Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience,* 3: 178-181.

DENEVAN, W. M. 1992. The Pristine Myth: The Landscape of the Americas in 1492. *Annals of the Association of American Geographers,* 82: 369-385.

DIAS, L. C. P., PIMENTA, F. M., SANTOS, A. B., COSTA, M. H. & LADLE, R. J. 2016. Patterns of land use, extensification, and intensification of Brazilian agriculture. *Global Change Biology*: 15.

DIETZ, T., OSTROM, E. & P.C., S. 2003. The struggle to govern the commons. *Science,* 302: 6.
DINIZ, C. G., SOUZA, A. A. D. A., SANTOS, D. C., DIAS, M. C., LUZ, N. C. D., MORAES, D. R. V. D., MAIA, J. S. A., GOMES, A. R., NARVAES, I. D. S., VALERIANO, D. M., MAURANO, L. E. P. & ADAMI, M. 2015. DETER-B: The New Amazon Near Real-Time Deforestation Detection System. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing,* 8: 3619-3628.
DOBERMANN, A., NELSON, R., BEEVER, D. & CROWLEY, E. 2013. Solutions for sustainable agriculture and food systems. Technical report for the post-2015 development agenda. New York: Sustainable Development Solutions Network (SDSN).
ELHORST, J. P. 2010. Applied Spatial Econometrics: Raising the Bar. *Spatial Economic Analysis,* 5: 9-28.
EVANS, T. P., MANIRE, A., DE CASTRO, F., BRONDIZIO, E. & MCCRACKEN, S. 2001. A dynamic model of household decision-making and parcel level landcover change in the eastern Amazon. *Ecological Modelling,* 143: 95-113.
FAO 2014. State of the World's Forests: Enhancing the socioeconomic benefits from forests. 133.
FAO 2015. The State of Food and Agriculture Social protection and agriculture: breaking the cycle of rural poverty. 151p.
FARIAS, M. H. C. S., BELTRÃO, N. E. S., SANTOS, C. A. & CORDEIRO, Y. E. M. 2018. Impacto dos assentamentos rurais no desmatamento da Amazônia. *Mercator,* 17: 20.
FEARNSIDE, P. M. 1983. Land-use Trends in the Brazilian Amazon Region as Factors in Accelerating Deforestation. *Environmental Conservation,* 10: 141-148.
FEARNSIDE, P. M. 1996. Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forest. *Forest Ecology and Management,* 80: 21-34.
FEARNSIDE, P. M. 2001. Land-Tenure Issues as Factors in Environmental Destruction in Brazilian Amazonia: The Case of Southern Pará. *World Development,* 29: 1361-1372.
FEARNSIDE, P. M. 2005. Deforestation in Brazilian Amazonia: History, Rates, and Consequences. *Conservation Biology,* 19: 680-688.
FEARNSIDE, P. M. & DE ALENCASTRO GRAÇA, P. M. L. 2006. BR-319: Brazil's Manaus-Porto Velho Highway and the Potential Impact of Linking the Arc of Deforestation to Central Amazonia. *Environmental Management,* 38: 705-716.
FEARNSIDE, P. M. & FIGUEIREDO, A. M. R. 2015. China's Influence on Deforestation in Brazilian Amazonia: a growing force in the State of Mato Grosso. *In:* INITIATIVE, G. E. G. (ed.) *WORKING GROUP ON DEVELOPMENT AND ENVIRONMENT IN THE AMERICAS.* Global Development and environment institute.
FEARNSIDE, P. M., FIGUEIREDO, A. M. R. & BONJOUR, S. C. M. 2013. Amazonian forest loss and the long reach of China's influence. *Environment, Development and Sustainability,* 15: 325-338.
FERRARO, P. J. 2009. Counterfactual thinking and impact evaluation in environmental policy. *New Directions for Evaluation,* 2009: 75-84.
FERRARO, P. J., MCINTOSH, C. & OSPINA, M. 2007. The effectiveness of the US endangered species act: An econometric analysis using matching methods. *Journal of Environmental Economics and Management,* 54: 245-261.
FREY, G., WEST, T., HICKLER, T., RAUSCH, L., GIBBS, H. & BÖRNER, J. 2018. Simulated Impacts of Soy and Infrastructure Expansion in the Brazilian Amazon: A Maximum Entropy Approach. *Forests,* 9: 600.
FROHN, R. C., DALE V.H. & JIMENEZ B.D. 1990. Colonization, road development and deforestation in the Brazilian Amazon Basin of Rondônia. Oak Ridge, Tennessee: Oak Ridge National Laboratory.
FUJISAKA, S., BELL, W., THOMAS, N., HURTADO, L. & CRAWFORD, E. 1996. Slash-and-burn agriculture, conversion to pasture, and deforestation in two Brazilian Amazon colonies. *Agriculture, Ecosystems and Environment,* 59: 115-130.
FUTEMMA, C. & BRONDÍZIO, E. S. 2003. Land Reform and Land-Use Changes in the Lower Amazon: Implications for Agricultural Intensification. *Human Ecology,* 31: 369-402.

GARCIA, R. A., SOARES-FILHO, B. S. & SAWYER, D. O. 2007. Socioeconomic dimensions, migration, and deforestation: An integrated model of territorial organization for the Brazilian Amazon. *Ecological Indicators,* 7: 719-730.
GARRETT, R. D., GARDNER, T. A., MORELLO, T. F., MARCHAND, S., BARLOW, J., EZZINE DE BLAS, D., FERREIRA, J., LEES, A. C. & PARRY, L. 2017. Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon. *Ecology and Society,* 22.
GARRETT, R. D., KOH, I., LAMBIN, E. F., LE POLAIN DE WAROUX, Y., KASTENS, J. H. & BROWN, J. C. 2018. Intensification in agriculture-forest frontiers: Land use responses to development and conservation policies in Brazil. *Global Environmental Change,* 53: 233-243.
GARRETT, R. D., LAMBIN, E. F. & NAYLOR, R. L. 2013a. Land institutions and supply chain configurations as determinants of soybean planted area and yields in Brazil. *Land Use Policy,* 31: 385-396.
GARRETT, R. D., LAMBIN, E. F. & NAYLOR, R. L. 2013b. The new economic geography of land use change: Supply chain configurations and land use in the Brazilian Amazon. *Land Use Policy,* 34: 265-275.
GIBBS, H. K. & SALMON, J. M. 2015. Mapping the world's degraded lands. *Applied Geography,* 57: 12-21.
GIBBS, H. K., WALKER, N. F., RAUSCH, L., MUNGER, J., SCHELLY, I., MORTON, D. C., NOOJIPADY, P., SOARES-FILHO, B., BARRETO, P. & MICOL, L. 2015. Brazil's Soy Moratorium. *Science,* 347: 377-378.
GLOBO 1988. Assassinato de Chico Mendes - http://memoriaglobo.globo.com/programas/jornalismo/coberturas/chico-mendes-assassinato/chico-mendes-assassinato-a-historia.htm. *In:* GLOBO, M. (ed.). Globo.
GOLGHER, A. B. & VOSS, P. R. 2016. How to Interpret the Coefficients of Spatial Models: Spillovers, Direct and Indirect Effects. *Spatial Demography,* 4: 175-205.
GOLLNOW, F., HISSA, L. D. B. V., RUFIN, P. & LAKES, T. 2018. Property-level direct and indirect deforestation for soybean production in the Amazon region of Mato Grosso, Brazil. *Land Use Policy,* 78: 377-385.
GRATWICKE, B. 2007. Poaching laws are useless without solid enforcement. *Nature,* 445: 147-147.
HAINMUELLER, J. 2012. Entropy Balancing for Causal Effects: A Multivariate Reweighting Method to Produce Balanced Samples in Observational Studies. *Political Analysis,* 20: 25-46.
HAINMUELLER, J. & XU, Y. 2013. ebalance: A Stata Package for Entropy Balancing. *Journal of Statistical Software,* 54: 18.
HALL, D. 2015. The political ecology of international agri-food systems. *In:* PERREAULT, T. B., GAVIN; MCCARTHY, JAMES (ed.) *Routledge Handbook of Political Ecology* Book Routledge International Handbooks.
HANNAH, L., MIDGLEY, G. U. Y., HUGHES, G. & BOMHARD, B. 2005. The View from the Cape: Extinction Risk , Protected Areas , and Climate Change. *BioScience,* 55: 12.
HANSEN, M. C., LOVELAND, T. R., KOMMAREDDY, A., EGOROV, A., CHINI, L., JUSTICE, C. O., TOWNSHEND, J. R. G., POTAPOV, P. V., MOORE, R., HANCHER, M., TURUBANOVA, S. A., TYUKAVINA, A., THAU, D., STEHMAN, S. V. & GOETZ, S. J. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science,* 342: 850.
HARGRAVE, J. & KIS-KATOS, K. 2013. Economic Causes of Deforestation in the Brazilian Amazon: A Panel Data Analysis for the 2000s. *Environmental and Resource Economics,* 54: 471-494.
HECHT, S. B. 1985. Environment, development and politics: Capital accumulation and the livestock sector in Eastern Amazonia. *World Development,* 13: 663-684.
HECHT, S. B. 1989. The Sacred Cow in the Green Hell: Livestock and Forest Conversion in the Brazilian Amazon. *Ecologist,* 19: 229-229.
HECHT, S. B. 1992. Logics of Livestock and Deforestation: The Case of Amazonia. *In:* DOWNING, T., HECHT, S., PEARSON, H. & DOWNING, C. G. (eds.) *Development or Destruction, The Conversion of Tropical Forest to Pasture in Latin America.* Boulder: Westview Press.

HECHT, S. B. 1993a. Brazil - landlessness, land speculation and pasture-led deforestation. *In:* COLCHESTER, M. & LOHMANN, L. (eds.) *The struggle for land and the fate of the forests.* World Rainforest Movement.
HECHT, S. B. 1993b. The Logic of Livestock and Deforestation in Amazonia. *BioScience,* 43: 687-695.
HECHT, S. B. 2010. The new rurality: Globalization, peasants and the paradoxes of landscapes. *Land Use Policy,* 27: 389.
HECHT, S. B. & SAATCHI, S. S. 2007. Globalization and Forest Resurgence: Changes in Forest Cover in El Salvador. *BioScience,* 57: 663-672.
HOBBS, R. J. 2005. The Future of Restoration Ecology : Challenges and Opportunities. *Restoration Ecology,* 13: 239-241.
HOBBS, R. J. & HARRIS, J. A. 2001. Restoration Ecology: Repairing the Earth's Ecosystems in the New Millennium. *Restoration Ecology,* 9: 239-246.
HOLL, K. D. & AIDE, T. M. 2011. When and where to actively restore ecosystems? *Forest Ecology and Management,* 261: 1558-1563.
HOLLAND, P. W. 1986. Statistics and Causal Inference. *Journal of the American Statistical Association,* 81: 16.
HOSONUMA, N., HEROLD, M., SY, D. V., FRIES, D. R. S., BROCKHAUS, M., VERCHOT, L., ANGELSEN, A. & ROMIJN, E. 2012. An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters,* 7: urn:issn:1748-9326.
HUMMEL, A. C. 2016. Deforestation in the Amazon: What is illegal and what is not? *Elementa: Science of the Anthropocene (2016),* 4.
IBAMA 2017. Amazônia Protege: MPF, Ibama e ICMBio propõem ações civis públicas para punir responsáveis por desmatamentos ilegais.: Available at http://www.ibama.gov.br/noticias/422-2017/1260-amazoniaprotege-mpf-ibama-e-icmbio-propoem-acoes-civis-publicas-para-punir-responsaveispor-desmatamentos-ilegais.
IBGE 2009. Censo Agropecuário de 2006. https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2006/segunda-apuracao: IBGE.
IBGE. 2014. *Municipality Agricultural Production (PAM, portuguese acronym)* [Online]. https://sidra.ibge.gov.br/tabela/1612: IBGE. [Accessed July 12 2018].
IBGE 2018. Censo Agropecuário de 2017. https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2017: IBGE.
IGLESIAS, J. R., SEMESHENKO, V., SCHNEIDER, E. M. & GORDON, M. B. 2012. Crime and punishment: Does it pay to punish? *Physica A: Statistical Mechanics and its Applications,* 391: 3942-3950.
INCRA 2012. Programa de Prevenção, Combate e Alternativas ao Desmatamento Ilegal em Assentamentos da Amazônia - PPCADI-Amazônia, "Programa Assentamentos Verdes". *In:* (INCRA), I. N. D. C. E. R. A. (ed.) 229 ed. Brasilia: Imprensa Nacional.
INCRA. 2018. *Agrarian Reform in numbers* [Online]. http://www.incra.gov.br/reforma_agraria: INCRA - National Institute for colonization and agrarian reform. [Accessed 20Nov2018 2018].
INPE 2015. Programa de monitoramento do desflorestamento na Amazônia Brasileira-PRODES. . *In:* INPE (ed.) (available at http://www.obt.inpe.br/prodes/index.php - accessed May 16th 2016) ed.
INPE. 2016a. *DETER-B* [Online]. http://www.inpe.br/cra/projetos_pesquisas/deterb.php: INPE. [Accessed 02Dec2018 2018].
INPE 2016b. Terraclass, 2014. Survey of land cover and land use in the Amazon. Executive Summary - Inpe and Embrapa. . *In:* EMBRAPA, I. A. (ed.) (available at http://www.inpe.br/cra/ terraclass2014.php. - accessed May 16th 2016) ed.
INPE 2017. Programa de monitoramento do desflorestamento na Amazônia Brasileira-PRODES. . *In:* INPE (ed.) (available at http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes - accessed Mar 14th 2018) ed.
INPE & EMBRAPA 2016. Levantamento de uso e cobertura da terra na Amazonia - Sumario executivo
IPCC 2014a. Climate Change 2014 Synthesis Report Summary for Policymakers - Fifth Assessment Report (AR5). 32p.

IPCC 2014b. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change *In:* MEYER., R. K. P. A. L. A. (ed.). Geneva, Switzerland: IPCC.

IPCC 2019. Climate Change and Land - Summary for Policymakers. IPCC.

IUCN. 2011. *Bonn Challenge* [Online]. http://www.bonnchallenge.org/. [Accessed March 15 2018].

JN, J. N. 2015. Homem considerado o maior desmatador da Amazônia é preso - Ezequiel Castanha. http://g1.globo.com/jornal-nacional/noticia/2015/02/homem-considerado-o-maior-desmatador-da-amazonia-e-preso.html: G1.

KAIMOWITZ, D. 2002. Amazon deforestation revisited. *Latin American Research Review,* 37: 221-236.

KAIMOWITZ, D. & ANGELSEN, A. 1998. Economic Models of Tropical Deforestation-A Review. *Center for International Forestry Research, Indonesia, CIFOR*: 139p.

KARL, T. R. & TREBERTH, K. E. 2005. What is climate change? *In:* LOVEJOY, T. E. & HANNAH, L. J. (eds.) *Climate change and biodiversity.* New Haven; London: Yale University Press.

KASTENS, J. H., BROWN, J. C., COUTINHO, A. C., BISHOP, C. R. & ESQUERDO, J. 2017. Soy moratorium impacts on soybean and deforestation dynamics in Mato Grosso, Brazil. *PLoS One,* 12: e0176168.

KINTISCH, E. 2007. Improved Monitoring of Rainforests Helps Pierce Haze of Deforestation. *Science,* 316: 536.

KIRBY, K. R., LAURANCE, W. F., ALBERNAZ, A. K., SCHROTH, G., FEARNSIDE, P. M., BERGEN, S., VENTICINQUE, E. M. & DA COSTA, C. 2006. The future of deforestation in the Brazilian Amazon. *Futures,* 38: 432-453.

KOCH, N., ZU ERMGASSEN, E. K. H. J., WEHKAMP, J., OLIVEIRA FILHO, F. J. B. & SCHWERHOFF, G. 2019. Agricultural Productivity and Forest Conservation: Evidence from the Brazilian Amazon. *American Journal of Agricultural Economics*.

KUHLMAN, K. M. 2005. *Roads, protected areas, and fires: Factors that influence deforestation of Chiquitano dry forest in eastern Bolivia.* Dissertation/Thesis, ProQuest Dissertations Publishing.

KUTNER, M., NACHTSHEIM, C. & NETER, J. 2004. *Applied linear regression models,* Boston, London: McGraw-Hill Education.

LAMBIN, E. F., FOLKE, C., GEORGE, P. S., HOMEWOOD, K., IMBERNON, J., LEEMANS, R., LI, X., MORAN, E. F., MORTIMORE, M., RAMAKRISHNAN, P. S., RICHARDS, J. F., TURNER, B. L., SKÅNES, H., STEFFEN, W., STONE, G. D., SVEDIN, U., VELDKAMP, T. A., VOGEL, C., XU, J., GEIST, H. J., AGBOLA, S. B., ANGELSEN, A., BRUCE, J. W., COOMES, O. T., DIRZO, R. & FISCHER, G. 2001. The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change,* 11: 261-269.

LAMBIN, E. F., GIBBS, H. K., HEILMAYR, R., CARLSON, K. M., FLECK, L. C., GARRETT, R. D., LE POLAIN DE WAROUX, Y., MCDERMOTT, C. L., MCLAUGHLIN, D., NEWTON, P., NOLTE, C., PACHECO, P., RAUSCH, L. L., STRECK, C., THORLAKSON, T. & WALKER, N. F. 2018. The role of supply-chain initiatives in reducing deforestation. *Nature Climate Change,* 8: 109-116.

LAMBIN, E. F. & MEYFROIDT, P. 2011. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America,* 108: 3465-3472.

LATAWIEC, A. E., STRASSBURG, B. B. N., BRANCALION, P. H. S., RODRIGUES, R. R. & GARDNER, T. 2015. Creating space for large-scale restoration in tropical agricultural landscapes. *Frontiers in Ecology and the Environment,* 13: 211-218.

LAUE, J. E. & ARIMA, E. Y. 2014. Spatially explicit models of land abandonment in the Amazon. *Journal of Land Use Science*.

LAURANCE, W. F. & BIERREGAARD, R. O. 1997. *Tropical forest remnants- Ecology, management, and conservation of fragmented communities. ,* Chicago, USA., The University of Chicago Press.

LAURANCE, W. F., CAMPBELL, M. J., ALAMGIR, M. & MAHMOUD, M. I. 2017. Road Expansion and the Fate of Africa's Tropical Forests. *Frontiers in Ecology and Evolution,* 5.

LAURANCE, W. F., SCHROTH, G., FEARNSIDE, P. M., BERGEN, S., VENTICINQUE, E. M. & DA COSTA, C. 2002. Predictors of Deforestation in the Brazilian Amazon. *Journal of Biogeography,* 29: 737-748.

LE POLAIN DE WAROUX, Y., GARRETT, R. D., GRAESSER, J., NOLTE, C., WHITE, C. & LAMBIN, E. F. 2017. The Restructuring of South American Soy and Beef Production and Trade Under Changing Environmental Regulations. *World Development*.

LE TOURNEAU, F. M. & BURSZTYN, M. 2010. Assentamentos rurais na Amazônia: contradições entre a política agrária e a política ambiental. *Ambiente & Sociedade,* 13: 20.

LEADER-WILLIAMS, N., ALBON, S. D. & BERRY, P. S. M. 1990. Illegal Exploitation of Black Rhinoceros and Elephant Populations: Patterns of Decline, Law Enforcement and Patrol Effort in Luangwa Valley, Zambia. *Journal of Applied Ecology,* 27: 1055-1087.

LEITE, F. L., CALDAS, M. M., SIMMONS, C., PERZ, S. G., ALDRICH, S. & WALKER, R. T. 2011. The social viability and environmental sustainability of direct action land reform settlements in the Amazon. *Environment, Development and Sustainability,* 13: 773-788.

LISA, L. R. & HOLLY, K. G. 2016. Property Arrangements and Soy Governance in the Brazilian State of Mato Grosso: Implications for Deforestation-Free Production. *Land,* 5: 7.

LORENA, R. B. & LAMBIN, E. F. 2009. The spatial dynamics of deforestation and agent use in the Amazon. *Applied Geography,* 29: 171-181.

LOVEJOY, T. E. & NOBRE, C. 2018. Amazon Tipping Point. *Science advances,* 4: eaat2340.

LUDEWIGS, T., D'ANTONA, A. D. O., BRONDÍZIO, E. S. & HETRICK, S. 2009. Agrarian Structure and Land-cover Change Along the Lifespan of Three Colonization Areas in the Brazilian Amazon. *World Development,* 37: 1348-1359.

LUI, G. H. 2013. Transição de modos de vida rurais na Amazônia brasileira: uma perspectiva longiudinal sobre diversificação da renda, atividades agrícolas e uso da terra entre pequenos produtores. *Tese (Doutorado) - Escola Superior de Agricultura "Luis de Queiroz". Centro de Energia Nuclear na Agricultura.* : 310p.

MACEDO, M. N., DEFRIES, R. S., MORTON, D. C., STICKLER, C. M., GALFORD, G. L. & SHIMABUKURO, Y. E. 2012. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *Proceedings of the National Academy of Sciences of the United States of America,* 109: 1341-1346.

MAGALHÃES, M. P. 2008. O mito da natureza selvagem. *In:* FURTADO, R. (ed.) *Coleção Amazônia: Origens.* São Paulo: Scientific American Brasil. Duetto Editorial

MAHAR, D. 1988. Government Policies and Deforestation in Brazil's Amazon Region. Washington, DC.: World Bank.

MARGULIS, S. 2003. Causes of Deforestation in the Brazilian Amazon. Brasilia: World Bank.

MARTIN, P. A., NEWTON, A. C. & BULLOCK, J. M. 2013. Carbon pools recover more quickly than plant biodiversity in tropical secondary forests. *Proceedings of the Royal Society B-Biological Sciences,* 280: 8.

MCALPINE, C. A., ETTER, A., FEARNSIDE, P. M., SEABROOK, L. & LAURANCE, W. F. 2009. Increasing world consumption of beef as a driver of regional and global change: A call for policy action based on evidence from Queensland (Australia), Colombia and Brazil. *Global Environmental Change,* 19: 21-33.

MCMANUS, J. F. 2004. A great grand-daddy of ice cores. *Nature,* 429: 611-612.

MELO, F. P. L., PINTO, S. R. R., BRANCALION, P. H. S., CASTRO, P. S., RODRIGUES, R. R., ARONSON, J. & TABARELLI, M. 2013. Priority setting for scaling-up tropical forest restoration projects: Early lessons from the Atlantic Forest Restoration Pact. *Environmental Science & Policy,* 33: 395-404.

MERRY, F., AMACHER, G. & LIMA, E. 2008. Land Values in Frontier Settlements of the Brazilian Amazon. *World Development,* 36: 2390-2401.

MERRY, F. & SOARES-FILHO, B. 2017. Will intensification of beef production deliver conservation outcomes in the Brazilian Amazon? *Elem Sci Anth,* 5: 24.

MEYFROIDT, P. 2013. Environmental cognitions, land change, and social-ecological feedbacks: an overview. *Journal of Land Use Science,* 8: 341-367.
MEYFROIDT, P., LAMBIN, E. F., ERB, K.-H. & HERTEL, T. W. 2013. Globalization of land use: Distant drivers of land change and geographic displacement of land use. *Current Opinion in Environmental Sustainability,* 5: 438-444.
MEYFROIDT, P., LAMBIN, E. F., MORTON, D. C., ROBIGLIO, V., CARLSON, K. M., FAGAN, M. E., GUTIERREZ-VELEZ, V. H., MACEDO, M. N., CURRAN, L. M., DEFRIES, R. S., DYER, G. A. & GIBBS, H. K. 2014. Multiple pathways of commodity crop expansion in tropical forest landscapes. *ENVIRONMENTAL RESEARCH LETTERS,* 9: 1-13.
MEYFROIDT, P., ROY CHOWDHURY, R., DE BREMOND, A., ELLIS, E. C., ERB, K. H., FILATOVA, T., GARRETT, R. D., GROVE, J. M., HEINIMANN, A., KUEMMERLE, T., KULL, C. A., LAMBIN, E. F., LANDON, Y., LE POLAIN DE WAROUX, Y., MESSERLI, P., MÜLLER, D., NIELSEN, J. Ø., PETERSON, G. D., RODRIGUEZ GARCÍA, V., SCHLÜTER, M., TURNER, B. L. & VERBURG, P. H. 2018. Middle-range theories of land system change. *Global Environmental Change,* 53: 52-67.
MILLS BUSA, J. H. 2013. Deforestation beyond borders: Addressing the disparity between production and consumption of global resources. *Conservation Letters,* 6: 192-199.
MILNER-GULLAND, E. J. & LEADER-WILLIAMS, N. 1992. A Model of Incentives for the Illegal Exploitation of Black Rhinos and Elephants: Poaching Pays in Luangwa Valley, Zambia. *Journal of Applied Ecology,* 29: 388-401.
MMA 2016. Plano de prevenção e controle do desmatamento na Amazônia e no Cerrado. *In:* DPCD (ed.). Brasilia: Ministério de Meio Ambiente.
MMA 2018. Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Cerrado (PPCerrado) e Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm) : fase 2016-2020 / Ministério do Meio Ambiente, Secretaria de Mudança do Clima e Florestas, Departamento de Florestas e Combate ao Desmatamento. Available: http://combateaodesmatamento.mma.gov.br/images/conteudo/Livro-PPCDam-e-PPCerrado_WEB_1.pdf. *In:* DESMATAMENTO, D. D. F. E. C. A. (ed.). Brasilia: MMA.
MORAN, E. F. 1981. *Developing the Amazon,* Bloomington, Indiana Univ. Press.
MORAN, E. F. 1993. Deforestation and Land Use in the Brazilian Amazon. *Human Ecology,* 21: 1-21.
MORAN, E. F., BRONDIZIO, E., MAUSEL, P. & WU, Y. 1994. Integrating Amazonian Vegetation, Land-Use, and Satellite Data. *BioScience,* 44: 329-338.
MORAN, E. F. & BRONDIZIO, E. S. 1998. Land-use change after deforestation in Amazonia. *In:* D. LIVERMAN, D., MORAN, E. F., RINDFUSS, R. R. & STERN, P. C. (eds.) *People and Pixels: Linking Remote Sensing and Social Science.* Washington DC: National Academy Press.
MORAN, E. F., BRONDIZIO, E. S., TUCKER, J. M., DA SILVA-FORSBERG, M. C., MCCRACKEN, S. & FALESI, I. 2000. Effects of soil fertility and land-use on forest succession in Amazônia. *Forest Ecology and Management,* 139: 93-108.
MORAN, E. F., PACKER, A., BRONDIZIO, E. & TUCKER, J. 1996. Restoration of vegetation cover in the eastern Amazon. *Ecological Economics,* 18: 41-54.
MORRISON, E. B. & LINDELL, C. A. 2011. Active or Passive Forest Restoration? Assessing Restoration Alternatives with Avian Foraging Behavior. *Restoration Ecology,* 19: 170-177.
MORTON, D. C., DEFRIES, R. S., SHIMABUKURO, Y. E., ANDERSON, L. O., ARAI, E., DEL BON ESPIRITO-SANTO, F., FREITAS, R. & MORISETTE, J. 2006. Cropland Expansion Changes Deforestation Dynamics in the Southern Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America,* 103: 14637-14641.
MOUTINHO, P., GUERRA, R. & AZEVEDO-RAMOS, C. 2016. Achieving zero deforestation in the Brazilian Amazon: What is missing? *Elementa: Science of the Anthropocene,* 4: 000125.
MULLAN, K., SILLS, E., PATTANAYAK, S. K. & CAVIGLIA-HARRIS, J. 2017. Converting Forests to Farms: The Economic Benefits of Clearing Forests in Agricultural Settlements in the Amazon. *Environmental and Resource Economics,* 71: 427-455.
NAGENDRA, H. 2007. Drivers of Reforestation in Human-Dominated Forests. *Proceedings of the National Academy of Sciences of the United States of America,* 104: 15218-15223.

NEEFF, T., LUCAS, R. M., DOS SANTOS, J. R., BRONDIZIO, E. S. & FREITAS, C. C. 2006. Area and Age of Secondary Forests in Brazilian Amazonia 1978-2002: An Empirical Estimate. *Ecosystems,* 9: 609-623.

NEPSTAD, D. 1997. Land-use in Amazonia and the Cerrado of Brazil: State of Knowledge and GIS Database.

NEPSTAD, D., DA MOTTA, R. S., ARMIJO, E., CASTELLO, L., BRANDO, P., HANSEN, M. C., MCGRATH-HORN, M., CARVALHO, O., HESS, L., MCGRATH, D., STICKLER, C., ALENCAR, A., AZEVEDO, A., SWETTE, B., BEZERRA, T., DIGIANO, M. & SHIMADA, J. 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *SCIENCE,* 344: 1118-1123.

NEPSTAD, D., SCHWARTZMAN, S., MCGRATH, D. G., STICKLER, C. M., LUBOWSKI, R., PIRIS-CABEZAS, P., RIVERO, S., ALENCAR, A., ALMEIDA, O., STELLA, O., SOARES-FILHO, B. S., MERRY, F., LIMA, A., MOUTINHO, P., CARTER, J., BOWMAN, M., CATTANEC, A. & RODRIGUES, H. 2009. The End of Deforestation in the Brazilian Amazon. *Science,* 326: 1350-1351.

NEPSTAD, D. C., STICKLER, C. M. & ALMEIDA, O. T. 2006. Globalization of the Amazon Soy and Beef Industries: Opportunities for Conservation. *Conservation Biology,* 20: 1595-1603.

NEPSTAD, D. C. & UHL, C. 1991. Recuperation of a Degraded Amazonian Landscape: Forest Recovery and Agricultural Restoration. *Ambio,* 20: 248-255.

NEPSTAD, D. C., UHL, C. & PEREIRA, C. A. 1996. A Comparative Study of Tree Establishment in Abandoned Pasture and Mature Forest of Eastern Amazonia. *Oikos,* 76: 25-39.

NUNES, S. S., BARLOW, J. O. S., GARDNER, T. A., SIQUEIRA, J. V., SALES, M. R. & SOUZA, C. M. 2015. A 22 year assessment of deforestation and restoration in riparian forests in the eastern Brazilian Amazon. *Environmental Conservation,* 42: 193-203.

OLIVEIRA, A. U. 1997. *A fronteira amazônica mato-grossense: grilagem, corrupção e violência.* Livre Docência, Universidade de São Paulo.

OPDAM, P. & WASCHER, D. 2004. Climate change meets habitat fragmentation: linking landscape and biogeographical scale levels in research and conservation. *Biological Conservation,* 117: 285-297.

OSTROM, E. 2007. A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences of the USA* 104: 15181-15187.

OSTROM, E., JANSSEN, M. A. & ANDERIES, J. M. 2007. Going beyond panaceas. *Proceedings of the National Academy of Sciences of the USA* 104: 15176-15178.

PACHECO, P. 2012. Actor and frontier types in the Brazilian Amazon: Assessing interactions and outcomes associated with frontier expansion. *Geoforum,* 43: 864-874.

PARISH, W. J., KEYES, V., BEADLES, C. & KANDILOV, A. 2017. Using entropy balancing to strengthen an observational cohort study design: lessons learned from an evaluation of a complex multi-state federal demonstration. *Health Services and Outcomes Research Methodology,* 18: 17-46.

PATUELLI, R., SCHANNE, N., GRIFFITH, D. A. & NIJKAMP, P. 2012. PERSISTENCE OF REGIONAL UNEMPLOYMENT: APPLICATION OF A SPATIAL FILTERING APPROACH TO LOCAL LABOR MARKETS IN GERMANY*. *Journal of Regional Science,* 52: 300-323.

PAULA, M., KAREN, D. H., JOSÉ MARÍA REY, B., HOLLY, P. J., PETER, C. J., DANIEL, M. & DAVID MORENO, M. 2017. A global review of past land use, climate, and active vs. passive restoration effects on forest recovery. *PLoS ONE,* 12: e0171368.

PEARSON, R. G. & DAWSON, T. P. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? . *Global Ecology and Biogeography* 12: 361-371.

PERZ, S. G. 2000. The Rural Exodus in the Context of Economic Crisis, Globalization and Reform in Brazil. *International Migration Review,* 34: 842-881.

PERZ, S. G. 2003. Social Determinants and Land Use Correlates of Agricultural Technology Adoption in a Forest Frontier: A Case Study in the Brazilian Amazon. *Human Ecology,* 31: 133-165.

PERZ, S. G. 2014. The promise and perils of roads. *Nature,* 513: 178.

PERZ, S. G., CALDAS, M. M., ARIMA, E. & WALKER, R. J. 2007. Unofficial Road Building in the Amazon: Socioeconomic and Biophysical Explanations. *Development and Change,* 38: 529-551.
PERZ, S. G., LEITE, F., SIMMONS, C., WALKER, R., ALDRICH, S. & CALDAS, M. 2010. Intraregional Migration, Direct Action Land Reform, and New Land Settlements in the Brazilian Amazon. *Bulletin of Latin American Research,* 29: 459-476.
PERZ, S. G., SHENKIN, A., BARNES, G., CABRERA, L., CARVALHO, L. A. & CASTILLO, J. 2012. Connectivity and Resilience: A Multidimensional Analysis of Infrastructure Impacts in the Southwestern Amazon. *Social Indicators Research,* 106: 259-285.
PERZ, S. G. & SKOLE, D. L. 2003a. Secondary forest expansion in the Brazilian Amazon and the refinement of forest transition theory. *SOCIETY & NATURAL RESOURCES,* 16: 277-294.
PERZ, S. G. & SKOLE, D. L. 2003b. Social determinants of secondary forests in the Brazilian Amazon. *Social Science Research,* 32: 25-60.
PFAFF, A., LAURANCE, W., KIRBY, K., ROBALINO, J., WALKER, R., ALDRICH, S., CALDAS, M., REIS, E., PERZ, S., BOHRER, C. & ARIMA, E. 2007. ROAD INVESTMENTS, SPATIAL SPILLOVERS, AND DEFORESTATION IN THE BRAZILIAN AMAZON. *Journal of Regional Science,* 47: 109-123.
PFAFF, A., ROBALINO, J., REIS, E. J., WALKER, R., PERZ, S., LAURANCE, W., BOHRER, C., ALDRICH, S., ARIMA, E., CALDAS, M. & KIRBY, K. 2018. Roads & SDGs, tradeoffs and synergies: learning from Brazil's Amazon in distinguishing frontiers. *Economics: The Open-Access, Open-Assessment E-Journal*.
PFAFF, A. & WALKER, R. 2010. Regional interdependence and forest "transitions": Substitute deforestation limits the relevance of local reversals. *Land Use Policy,* 27: 119-129.
PFAFF, A. S. P. 1999. What Drives Deforestation in the Brazilian Amazon?: Evidence from Satellite and Socioeconomic Data. *Journal of Environmental Economics and Management,* 37: 26-43.
PHALAN, B., BERTZKY, M., BUTCHART, S. H. M., DONALD, P. F., SCHARLEMANN, J. P. W., STATTERSFIELD, A. J. & BALMFORD, A. 2013. Crop Expansion and Conservation Priorities in Tropical Countries. *PLoS ONE,* 8: e51759.
PHALAN, B., GREEN, R. & BALMFORD, A. 2014. Closing yield gaps: perils and possibilities for biodiversity conservation. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences,* 369: 20120285.
PICOLI, M. C. A., CAMARA, G., SANCHES, I., SIMÕES, R., CARVALHO, A., MACIEL, A., COUTINHO, A., ESQUERDO, J., ANTUNES, J., BEGOTTI, R. A., ARVOR, D. & ALMEIDA, C. 2018. Big earth observation time series analysis for monitoring Brazilian agriculture. *ISPRS Journal of Photogrammetry and Remote Sensing,* 145: 328-339.
QUEIROZ, C., BEILIN, R., FOLKE, C. & LINDBORG, R. 2014. Farmland abandonment: threat or opportunity for biodiversity conservation? A global review. *Frontiers in Ecology and the Environment,* 12: 288-296.
REED, J., DEAKIN, L. & SUNDERLAND, T. 2015. What are 'Integrated Landscape Approaches' and how effectively have they been implemented in the tropics: a systematic map protocol. *Environmental Evidence,* 4: 1-2.
REYDON, B. P., FERNANDES, V. B. & TELLES, T. S., 2015. 2015. Land tenure in Brazil: The question of regulation and governance *Land Use Policy* 42: 509-516.
RODRIGUES, A. S. L., EWERS, R. M., PARRY, L., SOUZA, C., VERÍSSIMO, A. & BALMFORD, A. 2009a. Boom-and-Bust Development Patterns across the Amazon Deforestation Frontier. *Science,* 324: 1435-1437.
RODRIGUES, R. R., GANDOLFI, S., NAVE, A. G., ARONSON, J., BARRETO, T. E., VIDAL, C. Y. & BRANCALION, P. H. S. 2011. Large-scale ecological restoration of high-diversity tropical forests in SE Brazil. *Forest Ecology and Management,* 261: 1605-1613.
RODRIGUES, R. R., LIMA, R. A. F., GANDOLFI, S. & NAVE, A. G. 2009b. On the restoration of high diversity forests: 30 years of experience in the Brazilian Atlantic Forest. *Biological Conservation,* 142: 1242-1251.
ROITMAN, I., CARDOSO GALLI VIEIRA, L., BAIOCCHI JACOBSON, T. K., DA CUNHA BUSTAMANTE, M. M., SILVA MARCONDES, N. J., CURY, K., SILVA ESTEVAM, L., DA COSTA RIBEIRO, R. J., RIBEIRO,

V., STABILE, M. C. C., DE MIRANDA FILHO, R. J. & AVILA, M. L. 2018. Rural Environmental Registry: An innovative model for land-use and environmental policies. *Land Use Policy,* 76: 95-102.
RUDEL, T. K., COOMES, O. T., MORAN, E., ACHARD, F., ANGELSEN, A., XU, J. & LAMBIN, E. 2005. Forest transitions: towards a global understanding of land use change. *Global Environmental Change,* 15: 23-31.
RUDEL, T. K., DEFRIES, R., ASNER, G. P. & LAURANCE, W. F. 2009a. Changing drivers of deforestation and new opportunities for conservation. *Conservation Biology,* 23: 1396-1405.
RUDEL, T. K., LAMBIN, E. F., BIRKENHOLTZ, T., BAPTISTA, S., GRAU, R., CLARK, W. C., SCHNEIDER, L., URIARTE, M., TURNER, B. L., DEFRIES, R., LAWRENCE, D., GEOGHEGAN, J., HECHT, S. & ICKOWITZ, A. 2009b. Agricultural Intensification and Changes in Cultivated Areas, 1970-2005. *Proceedings of the National Academy of Sciences of the United States of America,* 106: 20675-20680.
RUDEL, T. K. & MEYFROIDT, P. 2014. Organizing anarchy: The food security-biodiversity-climate crisis and the genesis of rural land use planning in the developing world. *Land Use Policy,* 36: 239-247.
SANTOS, A. & COSTA, M. 2018. Do Large Slaughterhouses Promote Sustainable Intensification of Cattle Ranching in Amazonia and the Cerrado? *Sustainability,* 10: 3266.
SCBD 2003. Interlinkages between biological diversity and climate change. Advice on the integration of biodiversity considerations into the implementation of the United Nations Framework Convention on Climate Change and its Kyoto protocol. Montreal: Secretariat of the Convention on Biological Diversity.
SCBD 2010a. Global Biodiversity Outlook 3. Montréal: Secretariat of the Convention on Biological Diversity
SCBD 2010b. Strategic Plan for Biodiversity 2011–2020 and the Aichi Targets “Living in Harmony with Nature”. Secretariat of the Convention on Biological Diversity.
SCBD 2014. Global Biodiversity Outlook 4. Montréal: Secretariat of the Convention on Biological Diversity.
SCHIELEIN, J. & BÖRNER, J. 2018. Recent transformations of land-use and land-cover dynamics across different deforestation frontiers in the Brazilian Amazon. *Land Use Policy,* 76: 81-94.
SCHMITT, J. 2015. *Crime sem castigo: a efetividade da fiscalização ambiental para o controle do desmatamento ilegal na Amazônia.* PhD, Universidade de Brasilia.
SCHMITT, J. & SCARDUA, F. P. 2015. The environmental decentralization and the enforcement of Amazon deforestation. *Revista de Administração Pública,* 49: 1121.
SHOO, L. P., SCARTH, P., SCHMIDT, S. & WILSON, K. A. 2013. Reclaiming Degraded Rainforest: A Spatial Evaluation of Gains and Losses in Subtropical Eastern Australia to Inform Future Investment in Restoration. *Restoration Ecology,* 21: 481-489.
SIECK, M., IBISCH, P. L., MOLONEY, K. A. & JELTSCH, F. 2011. Current models broadly neglect specific needs of biodiversity conservation in protected areas under climate change. *BMC ecology* [Online], 11. Available: http://download.springer.com/static/pdf/24/art%253A10.1186%252F1472-6785-11-12.pdf?originUrl=http%3A%2F%2Fhttp%3A%2F%2Fbmcecol.biomedcentral.com%2Farticle%2F10.1186%2F1472-6785-11-12&token2=exp=1464651006~acl=%2Fstatic%2Fpdf%2F24%2Fart%25253A10.1186%25252F1472-6785-11-12.pdf*~hmac=6bd35ec660912866fbf152d14a49a31f2ffabd1f2e862c08c2045ef04f35d6b9 [Accessed 31/05/2016].
SILVA, D. C. C., RODRIGUES, M., CAMPOS, Í. & FARIA, A. M. D. M. 2017. The Role of Market Institutions in Reducing Amazon Deforestation: The Case of the Soy Moratorium. *EALR,* 8: 15.
SIMMONS, C. S., WALKER, R. T., ARIMA, E. Y., ALDRICH, S. P. & CALDAS, M. M. 2007. The Amazon Land War in the South of Pará. *Annals of the Association of American Geographers,* 97: 567-592.

SMITH, P., M. BUSTAMANTE, H. A., H. CLARK, H. DONG, E.A. ELSIDDIG, H. HABERL, R. HARPER, J. HOUSE, M. JAFARI, O. MASERA, C. MBOW, N.H. RAVINDRANATH, C.W. RICE, C. ROBLEDO ABAD, A. ROMANOVSKAYA, F. SPERLING, AND F. TUBIELLO, BUSTAMANTE, M., AHAMMAD, H., CLARK, H., DONG, H., ELSIDDIG, E. A., HABERL, H., HARPER, R., HOUSE, J., JAFARI, M., MASERA, O., MBOW, C., RAVINDRANATH, N. H., RICE, C. W., ABAD, C. R., ROMANOVSKAYA, A., SPERLING, F. & TUBIELLO, F. 2014. Agriculture, Forestry and Other Land Use (AFOLU). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*

SOARES-FILHO, B., HISSA, L., SILVESTRINI, R., MARETTI, C., DEFRIES, R. S., MOUTINHO, P., NEPSTAD, D., ANDERSON, A., RODRIGUES, H., GARCIA, R., DIETZSCH, L., MERRY, F. & BOWMAN, M. 2010. Role of Brazilian Amazon protected areas in climate change mitigation. *Proceedings of the National Academy of Sciences of the United States of America,* 107: 10821-10826.

SOARES-FILHO, B., RAJÃO R., MACEDO M., CARNEIRO A., COSTA W., COE M., H, R. & A., A. 2014. Cracking Brazil´s Forest Code. *Science* 344: 363-364.

SOARES-FILHO, B., SCHLESINGER, P., MCGRATH, D., NEPSTAD, D. C., CURRAN, L., CERQUEIRA, G. C., GARCIA, R. A., RAMOS, C. A., VOLL, E., MCDONALD, A. & LEFEBVRE, P. 2005. Cenários de desmatamento para a Amazônia. *Estudos Avançados,* 19: 137-152.

SOARES-FILHO, B. S., SCHLESINGER, P., NEPSTAD, D. C., CURRAN, L. M., CERQUEIRA, G. C., GARCIA, R. A., RAMOS, C. A., VOLL, E., MCDONALD, A. & LEFEBVRE, P. 2006. Modelling conservation in the Amazon basin. *Nature,* 440: 520-523.

SOARES-FILHO, B., ALENCAR, A., NEPSTAD, D., CERQUEIRA, G., VERA DIAZ, M. D. C., RIVERO, S., SOLÓRZANO, L. & VOLL, E. 2004. Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: the Santarém–Cuiabá corridor. *Global Change Biology,* 10: 745-764.

SOLER, L. D. S., ESCADA, M. I. S. & VERBURG, P. H. 2009. Quantifying deforestation and secondary forest determinants for different spatial extents in an Amazonian colonization frontier (Rondonia). *Applied Geography,* 29: 182-193.

SPAROVEK, G., BARRETTO, A. G. D. O. P., MATSUMOTO, M. & BERNDES, G. 2015. Effects of Governance on Availability of Land for Agriculture and Conservation in Brazil. *Environmental Science & Technology,* 49: 10285-10293.

SPAROVEK, G., BERNDES, G., BARRETTO, A. G. D. O. P., KLUG, I. L. F., INSTITUTIONEN FÖR ENERGI OCH MILJÖ, F. R., DEPARTMENT OF, E., ENVIRONMENT, P. R. T., CHALMERS UNIVERSITY OF, T. & CHALMERS TEKNISKA, H. 2012. The revision of the brazilian forest act: Increased deforestation or a historic step towards balancing agricultural development and nature conservation? *Environmental Science and Policy,* 16: 65-72.

SPAROVEK, G., GUIDOTTI, V., GUEDES PINTO, L. F., BERNDES, G., BARRETTO, A., CERIGNONI, F. & PINTO, L. F. G. 2018. Asymmetries of cattle and crop productivity and efficiency during Brazil's agricultural expansion from 1975 to 2006. *Elementa,* 6.

SPERA, S. A., COHN, A. S., VANWEY, L. K., MUSTARD, J. F., RUDORFF, B. F., RISSO, J. & ADAMI, M. 2014. Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. *ENVIRONMENTAL RESEARCH LETTERS,* 9: 1-12.

STRASSBURG, B. B. N., BROOKS, T., FELTRAN-BARBIERI, R., IRIBARREM, A., CROUZEILLES, R., LOYOLA, R., LATAWIEC, A. E., OLIVEIRA FILHO, F. J. B., SCARAMUZZA, C. A. M., SCARANO, F. R., SOARES-FILHO, B. & BALMFORD, A. 2017. Moment of truth for the Cerrado hotspot. *Nat Ecol Evol,* 1: 99.

STUDENMUND, A. H. 2014. *Using econometrics : a practical guide*, Harlow, Essex : Pearson, [2014] ©2014.

SUTINEN, J. G. 1987. Enforcement of the MFMCA: an economist's perspective. *Marine Fisheries Review,* 49: 8.

TAITSON, R. 2011. The role of law enforcement in the decrease of deforestation in the Brazilian Amazon. Dissertation MA Degree at King´s College London – Department of War Studies. 64p.
THOMSON, A. M., ELLIS, E. C., GRAU, H. R., KUEMMERLE, T., MEYFROIDT, P., RAMANKUTTY, N. & ZELEKE, G. 2019. Sustainable intensification in land systems: trade-offs, scales, and contexts. *Current Opinion in Environmental Sustainability,* 38: 37-43.
THUILLER, W., LAVOREL, S., ARAÚJO, M. B., SYKES, M. T. & PRENTICE, I. C. 2005. Climate change threats to plant diversity in Europe. . *Proceedings of the National Academy of Sciences of the United States of America* 102: 8245-8250.
TOLLEFSON, J. 2012. Brazil unveils tool to track emissions: carbon releases lag behind Amazon deforestation. *Nature,* 488: 570.
TOLLEFSON, J. 2015. Battle for the Amazon. *Nature,* 520: 20-23.
TUBIELLO, F. N., SALVATORE, M., ROSSI, S., FERRARA, A., FITTON, N. & SMITH, P. 2013. The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters,* 8: 1-10.
TURNER, B. L., LAMBIN, E. F. & REENBERG, A. 2007. The Emergence of Land Change Science for Global Environmental Change and Sustainability. *Proceedings of the National Academy of Sciences of the United States of America,* 104: 20666-20671.
UHL, C., BARRETO, P., VERÍSSIMO, A., VIDAL, E., AMARAL, P., BARROS, A. C., SOUZA, C., JOHNS, J. & GERWING, J. 1997. Natural Resource Management in the Brazilian Amazon. *BioScience,* 47: 160-168.
UN 2014. Forest Declaration. (available at http://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/07/New-York-Declaration-on-Forest-%E2%80%93-Action-Statement-and-Action-Plan.pdf - accessed May 13th 2016). United Nations.
UN 2015. Sustainable Developmento Goals. (available at http://www.un.org/sustainabledevelopment/sustainable-development-goals/ - accessed May 13th 2016): United Nations.
VAN DE STEEG, J. A., SPAROVEK, G., RANIERI, S. B. L., MAULE, R. F., COOPER, M., DOURADO NETO, D. & ALVES, M. C. 2006. Environmental impact of the Brazilian Agrarian Reform process from 1985 to 2001. *Scientia Agricola,* 63: 176-183.
VAN MARLE, M. J., FIELD, R. D., VAN DER WERF, G. R., ESTRADA DE WAGT, I. A., HOUGHTON, R. A., RIZZO, L. V., ARTAXO, P. & TSIGARIDIS, K. 2017. Fire and deforestation dynamics in Amazonia (1973-2014). *Global Biogeochem Cycles,* 31: 24-38.
VANWEY, L. K., GUEDES, G. R. & D'ANTONA, Á. O. 2012. Out-migration and land-use change in agricultural frontiers: insights from Altamira settlement project. *Population and Environment,* 34: 44-68.
VERBURG, P. H. & SOLER, L. D. S. 2010. Combining remote sensing and household level data for regional scale analysis of land cover change in the Brazilian Amazon. *Regional Environmental Change,* 10: 371-386.
VIEIRA, I. C. G., GARDNER, T., FERREIRA, J., LEES, A. C. & BARLOW, J. 2014. Challenges of governing second-growth forests: A case study from the Brazilian Amazonian state of Pará. *Forests,* 5: 1737-1752.
VOS, C. C., BERRY, P., OPDAM, P., BAVECO, H., NIJHOF, B., HANLEY, J. O. & BELL, C. 2008. Adapting landscapes to climate change: examples of climate-proof ecosystem networks and priority adaptation zones. *Journal of Applied Ecology* 45: 1722-1731.
WALKER, R., ARIMA, E., MESSINA, J., SOARES-FILHO, B., PERZ, S., VERGARA, D., SALES, M., PEREIRA, R. & CASTRO, W. 2013. Modeling spatial decisions with graph theory: logging roads and forest fragmentation in the Brazilian Amazon. *Ecological Applications,* 23: 239-254.
WALKER, R., MORAN, E. & ANSELIN, L. 2000. Deforestation and Cattle Ranching in the Brazilian Amazon: External Capital and Household Processes. *World Development,* 28: 683-699.

WALKER, R., PERZ, S., CALDAS, M. & SILVA, L. G. T. 2002. Land Use and Land Cover Change in Forest Frontiers: The Role of Household Life Cycles. *International Regional Science Review,* 25: 169-199.
WCED, W. C. O. E. A. D. 1987. Our common future.
WEINHOLD, D. & REIS, E. 2008. Transportation costs and the spatial distribution of land use in the Brazilian Amazon. *Global Environmental Change,* 18: 54-68.
WILCOX, B. A. & ELLIS, B. 2006. Forests and emerging infectious diseases of humans. *Unasylva,* 57: 8.
WITNESS, G. 2018. Deadliest year on record for land and environmental defenders, as agribusiness is shown to be the industry most linked to killings. https://www.globalwitness.org/en/press-releases/deadliest-year-record-land-and-environmental-defenders-agribusiness-shown-be-industry-most-linked-killings/.
WORTLEY, L., HERO, J. M. & HOWES, M. 2013. Evaluating Ecological Restoration Success: A Review of the Literature. *restoration ecology. Volume 21:Issue 5(2013:Sep.); 201309; 537-543*.
ZAHAWI, R. A., REID, J. L. & HOLL, K. D. 2014. Hidden Costs of Passive Restoration. *Restoration Ecology,* 22: 284-287.
ZARIN, D. J., DUCEY, M. J., TUCKER, J. M. & SALAS, W. A. 2001. Potential Biomass Accumulation in Amazonian Regrowth Forests. *Ecosystems,* 4: 658-668.
ZHAO, Q. & PERCIVAL, D. 2015. Entropy balancing is doubly robust. 5.
ZU ERMGASSEN, E. K. H. J., WILLIAMS, D. R. & BALMFORD, A. 2014. Livestock: tackle demand and yields. *Nature,* 508: 186-186.

9 Appendix

9.1 Brazilian Government open source information and databases to support the development of this study.

Organization	Dataset	Description	Access	Time series
Brazilian Environmental Agency (Ibama)	Surveillance database (SICAFI)	Results of the inspection operations carried out by IBAMA, including processes, fines, location, values, arrested materials, latitude/longitude etc.	Public (web page)	Daily since 198
	https://servicos.ibama.gov.br/ctf/publico/areasembargadas/ConsultaPublicaAreasEmbargadas.php			
	Embargoed areas	Public web based system with embargoed areas and its metadata.	Public (web page)	Daily since 2005
	https://servicos.ibama.gov.br/ctf/publico/areasembargadas/ConsultaPublicaAreasEmbargadas.php			
	Unpaved roads	Unofficial roads opened by offenders illegally in the Amazon	Restricted to officials of Ibama	No
	http://siscom.ibama.gov.br/			
Ministry of the Environment (MMA)/ Brazilian Forest Service (SFB)	Rural Environmental Registry System database (SICAR)	Information about the rural property: limits, areas used for production, legal reserve and permanent preservation . Also, highlights the areas to be recovered according to the current New Forest Code.	Public (web page)	Since 2012
	http://www.car.gov.br/publico/imoveis/index			

Organization	Dataset	Description	Access	Time series
Ministry of the Environment (MMA)/ Chico Mendes Institute for Biodiversity Conservation (ICMBio)	Protected Areas database	All information regarding Federal, state, county and private protected areas.	Public (web page)	
	http://mapas.mma.gov.br/i3geo/datadownload.htm			
National Institute for space research (INPE)	Amazon annual deforestation database (PRODES)	New deforested areas in the Brazilian Legal Amazon forests	Public (web page)	Yearly since 1988
	http://www.dpi.inpe.br/prodesdigital/prodes.php			
	Land use change (Terraclass Study)	Land use change classification (pasture, agriculture, natural restoration, mining, water, clouds, cities etc.) for all deforested areas in the Amazon.	Public (web page)	2004, 2008, 2010,2012, 2014
	http://www3.inpe.br/cra/projetos_pesquisas/dados_terraclass.php			
	Precipitation, temperature and slope	Climatic and surface data	Public access	Variable
	http://www.dpi.inpe.br/Ambdata/English/			
National Institute for Colonization and	Settlements database	Spatial data from existing agrarian reform settlements including total area and each beneficiary plot.	Public (web page)	Daily update
	http://acervofundiario.incra.gov.br/geodownload/geodados.php			

Organization	Dataset	Description	Access	Time series
Agrarian Reform (INCRA)	Public Lands (vacant lands) database	State-owned but that are not applied to any public use, yet. ("Terras Devolutas")	Available by request	Daily update
	http://acervofundiario.incra.gov.br/geodownload/geodados.php			
Brazilian Institute of geography and statistics (IBGE)	Political borders (Municipal, states and federal)	Database with all the political borders of Brazil	Public (web page)	
	https://downloads.ibge.gov.br/downloads_geociencias.htm			
	Brazilian biogeographical region	Brazil has six biogeographical regions: Amazon, Cerrado (tropical savannas), Caatinga (xeric shrubland), Pantanal (wetland areas), Atlantic Forests and Pampa (grass lands)	Public (web page)	
	https://downloads.ibge.gov.br/downloads_geociencias.htm			
	Natural features and others	Rivers, soils, geology, precipitation, official roads,	Public (web page)	
	https://downloads.ibge.gov.br/downloads_geociencias.htm			
	Agriculture and livestock census	Includes municipal data for rural production and productivity (annual and perennial agriculture and livestock) and many other indicators of economic and social development.	Public (web page)	
	https://sidra.ibge.gov.br/acervo#/S/Q			
	SIDRA database	Municipal Agricultural Research (PAM)	Public	

Organization	Dataset	Description	Access	Time series
			(web page)	
		Municipal Livestock Research data (PPM)	Public (web page)	
		Municipal Plant Production and Forestry (PEVS)	Public (web page)	
	Economic indicators database	Per capita-GDP, GDP, inflation, household incomes, currency exchange rates etc.	Public (web page)	
	Population Census	Social indicators: education, health, employment etc.	Public (web page)	
	https://sidra.ibge.gov.br/acervo#/S/Q			
Indigenous people National Foundation	Indigenous territories database	Geographic limits of indigenous territories	Public (web page)	
	http://www.funai.gov.br/index.php/servicos/geoprocessamento			
Center for advanced studies in applied economics (CEPEA/ESALq)	Commodities prices database	Information about national and international market prices of commodities (soy, maize, beef etc.)	Public (web page)	
	https://www.cepea.esalq.usp.br/br			

Organization	Dataset	Description	Access	Time series
Institute for economics applied research (IPEA)	Economic database http://www.ipeadata.gov.br/Default.aspx	Economic indicators and indices related to public policies implementation.	Public (web page)	
Brazilian Central Bank	Loans for agriculture development database https://www.bcb.gov.br/?RELRURAL	includes information on the subsidized loans for agribusiness and family farming, such as "Harvest Plan" (MAPA[39]) and PRONAF/MDA[40], respectively.	Available by request	1999-2017

[39] MAPA – Ministry of Agriculture, Livestock and Supply
[40] PRONAF/MDA – National Program for strengthening Smallholders Agriculture/Ministry of Agrarian Development.

9.2 Supplement material – Chapter 2

Table S 2.1 – Percentage of deforestation by categories of use in the period 2004-2014. Categories: protected areas (strict preservation and sustainable use), indigenous lands, settlements, federal public lands (without allocation), private areas and others. (Sources: MMA, FUNAI, INCRA and MDA)

Year	Indigenous lands	Protected Areas		Settlements	Undesignated Federal Public lands*	Private areas /Others
		Strict Preservation	Sustainable use			
2004	2.5%	2.0%	5.0%	19.2%	25.1%	46.2%
2005	2.1%	1.2%	4.4%	21.3%	24.6%	46.4%
2006	2.1%	1.2%	6.9%	24.9%	29.4%	35.6%
2007	2.3%	0.9%	9.3%	25.0%	28.0%	34.5%
2008	3.4%	1.0%	5.5%	27.6%	27.0%	35.6%
2009	5.1%	1.0%	8.8%	33.1%	25.0%	27.1%
2010	4.7%	0.9%	7.5%	32.7%	24.8%	29.5%
2011	4.1%	0.6%	5.9%	34.2%	27.0%	28.2%
2012	3.6%	0.9%	6.9%	31.6%	25.1%	31.9%
2013	3.0%	0.6%	8.4%	31.4%	23.8%	32.8%
2014	1.9%	0.4%	9.0%	31.1%	22.7%	34.8%

*Public lands exclude overlap areas with PA, IL and Settlements

Table S 2.2 – Land use description of thematic classes mapped by Terraclass project, adapted from Almeida et al. (2016)

Thematic categories	Description
Annual crop	Extensive areas with predominance of annual crops, specially grains, highly technological such as certified seeds, enriched soil, chemicals, fertilizers, mechanization among other resources.
Non-observed areas	Areas not possible to be interpreted due to clouds or cloud shade at the moment of the satellite overpass or recently burned areas.
Urban areas	Population concentration forming small inhabited places, villages and cities that present differentiated infrastructure from the rural areas with street design and higher density of dwellings such as houses, buildings and other public spaces.
Mining	Areas of mineral extraction with the presence of bare soil and deforestation in the proximity of water bodies.
Mosaic of uses (occupation)	Characterized by land cover units that, due to the spatial resolution of the satellite images, cannot be broken down further into specific components. For example, this classification might include family agriculture practiced in conjunction with the traditional cattle raising.
Others	Areas not encompassed by other categories such as rocky or mountain outcrops, river shores and sand banks, among others.
Pasture with exposed soil (dirty)	Pasture areas, exhibiting signs of severe degradation, containing at least 50% bare soil.
Herbaceous pasture (clean)	Pasture in productive process with predominance of herbage and coverage between 90 and 100% by different species of grass.
Shrubby pasture (dirty)	Areas of pasture in productive process with predominance of herbage and coverage by species of grass between 50% and 80% associated to the presence of shrubby vegetation with coverage between 20% and 50%.
Pasture with vegetation regrowth (dirty)	Areas that were clear-cut, later developed as pasture and are at the beginning of a regenerative process containing shrubs and early successional vegetation.
Reforestation*	Large geometric homogeneous plantation of tree species, like Parica (*Schizolobium parahyba*), Teca (*Tectona grandis*) e Eucalipto (*Eucalyptus sp*). Similar to secondary vegetation.
Secondary vegetation	Areas that were clear-cut and are at an advanced stage of regeneration with trees and shrubs. Includes areas that were used for forestry (silviculture) or permanent agriculture with use of native or exotic species.
Water**	Water bodies: rivers, lakes, dam reservoir are part of the mask.
Clouds**	Clouds and clouds shadows on the ground are a constant presence in the amazon region. It is the reason for images selection in less cloudy period (july-september).

* Reforestation started to be mapped only in 2010. Thus, it is an addition to Almeida et al. (2016)
** They are represented here for the benefit of the reader that they were considered in the high resolution mapping.

Table S 2.3 – Land use and land cover of annual crops, pastures: clean and dirty, secondary vegetation, in km2, mapped at the property level according to the forest code three size categories: small, medium and large, by the nine states of the Legal Amazon. (Sources: MMA and Terraclass (INPE-EMBRAPA))

Thematic category	Property size	Acre					Amazonas					Amapa				
		2004	2008	2010	2012	2014	2004	2008	2010	2012	2014	2004	2008	2010	2012	2014
Crops	small	0	0	0	1	6	0	6	4	3	13	0	0	0	0	0
	med	0	0	3	5	25	0	6	2	6	3	0	0	0	0	0
	large	0	0	0	19	34	44	78	27	40	75	0	0	0	0	0
Herbaceous pasture	small	6,476	7,779	8,414	8,330	8,115	1,618	2,708	2,349	3,233	3,367	30	90	26	26	92
	med	946	1,081	1,114	1,072	1,099	553	799	909	960	934	16	41	13	14	31
	large	3,084	3,287	3,595	3,401	3,704	864	1,556	1,820	1,951	2,042	14	38	25	13	50
Other pastures	small	2,132	953	613	1,486	2,436	1,131	1,289	1,855	1,176	1,608	62	113	97	47	150
	med	283	119	117	201	248	325	384	273	206	306	12	32	32	14	37
	large	904	510	326	643	653	769	838	465	412	450	28	61	25	13	39
Secondary vegetation	small	1,233	2,045	2,632	2,213	1,851	2,450	3,185	3,525	3,687	3,380	177	215	248	357	317
	med	254	453	567	517	465	417	526	556	624	618	31	60	72	95	77
	large	751	1,193	1,495	1,366	1,223	1,549	1,977	2,053	2,184	2,145	263	312	120	150	128
Other uses	small	1,048	1,362	789	883	873	1,381	1,179	996	1,054	1,563	35	157	70	54	112
	med	208	251	183	253	290	251	104	116	125	178	7	15	15	15	32
	large	370	533	335	415	458	595	400	380	405	588	13	18	47	22	64

Table S 2.3 (cont.) – Land use and land cover of annual crops, pastures: clean and dirty, secondary vegetation, in km2, mapped at the property level according to the forest code three size categories: small, medium and large, by the nine states of the Legal Amazon. (Sources: MMA and Terraclass (INPE-EMBRAPA))

Thematic category	Property size	Mato Grosso					Pará					Rondônia				
		2004	2008	2010	2012	2014	2004	2008	2010	2012	2014	2004	2008	2010	2012	2014
Crops	small	3,209	5,859	6,366	7,251	7,139	170	441	936	910	850	167	922	1,467	855	1,354
	med	5,053	7,793	8,619	9,095	9,238	126	413	792	812	799	61	138	172	176	232
	large	9,293	18,228	20,106	22,132	24,243	268	980	1,660	1,592	1,748	126	447	547	533	738
Herbaceous pasture	small	35,864	37,023	42,335	41,400	43,754	39,332	53,527	51,722	54,281	60,125	33,990	43,133	42,862	44,995	46,785
	med	15,737	15,978	17,348	16,347	17,025	16,576	20,999	20,441	20,442	22,394	4,696	5,817	5,680	5,854	6,227
	large	59,874	58,948	63,044	58,373	58,711	32,284	40,595	37,681	38,177	42,600	6,064	6,707	6,221	6,377	6,843
Other pastures	small	8,089	9,387	5,310	7,153	5,847	23,324	18,429	25,289	17,063	23,707	9,765	9,303	7,562	5,179	5,198
	med	3,723	4,558	2,419	3,326	2,566	6,715	6,174	8,142	5,664	6,978	1,324	1,345	1,393	841	839
	large	12,914	14,560	8,128	11,624	9,137	14,014	12,973	16,144	11,385	13,208	1,398	1,505	1,816	1,147	991
Secondary vegetation	small	5,289	7,575	8,898	8,334	8,003	17,980	24,337	27,331	27,329	26,670	6,956	9,480	10,671	12,538	10,683
	med	3,053	4,470	5,049	4,857	4,998	5,549	7,309	8,045	7,954	7,812	973	1,332	1,479	1,803	1,574
	large	9,430	15,566	16,912	16,790	17,327	13,759	18,790	19,772	18,076	19,234	1,003	1,532	1,704	2,304	1,933
Other uses	small	3,971	3,500	943	1,297	1,663	9,852	7,118	6,518	3,359	4,639	7,291	1,501	2,057	1,962	3,078
	med	2,388	549	261	347	471	2,653	1,556	924	616	840	697	127	82	191	193
	large	7,007	1,742	671	1,046	1,521	4,877	2,900	3,316	2,846	3,512	725	159	190	288	430

Table S 2.3 (cont.) – Land use and land cover of annual crops, pastures: clean and dirty, secondary vegetation, in km2, mapped at the property level according to the forest code three size categories: small, medium and large, by the nine states of the Legal Amazon. (Sources: MMA and Terraclass (INPE-EMBRAPA))

Thematic category	Property size	Maranhão					Roraima					Tocantins				
		2004	2008	2010	2012	2014	2004	2008	2010	2012	2014	2004	2008	2010	2012	2014
Crops	small	3	24	77	55	124	0	2	1	1	1	3	16	16	8	9
	med	12	40	56	68	161	0	6	4	0	0	0	15	18	6	9
	large	18	102	200	71	226	0	5	7	2	6	2	46	50	26	82
Herbaceous pasture	small	12,662	10,371	9,266	11,766	14,775	1,110	909	580	1,004	1,702	3,687	3,878	4,820	4,565	5,234
	med	3,668	3,551	3,122	3,674	3,978	306	349	276	275	460	2,795	2,562	3,191	2,893	3,315
	large	9,212	7,038	5,228	6,770	8,534	245	340	242	210	398	6,418	5,162	6,639	5,804	6,727
Other pastures	small	5,572	6,066	10,973	7,065	6,493	1,133	1,070	1,150	534	751	2,651	1,676	862	1,364	805
	med	1,032	1,061	2,076	1,210	1,276	159	144	225	140	116	1,206	996	396	765	366
	large	2,850	2,891	5,284	4,308	3,740	123	90	161	132	68	1,413	2,120	570	1,387	598
Secondary vegetation	small	2,495	6,152	5,799	7,318	8,052	544	1,152	1,500	1,657	1,653	832	2,178	2,042	1,844	1,770
	med	640	1,304	1,157	1,301	1,461	127	198	265	290	317	454	1,132	1,084	990	1,031
	large	2,075	4,678	3,647	4,816	5,280	77	112	159	173	183	740	1,807	1,765	1,690	1,729
Other uses	small	1,083	1,842	2,213	779	1,217	504	786	705	326	277	202	89	84	52	113
	med	232	184	195	125	165	55	81	50	50	37	52	20	15	23	32
	large	869	1,415	1,093	529	746	28	42	22	39	15	91	20	28	67	80

9.3 Priority municipality list

IBGE Code	State	Municipality	In (year)	In (Legal Act)	Out (year)	Out (Legal Act)
5100250	MT	ALTA FLORESTA	2008	Ordinance n 28/2008	2012	Ordinance n 187/2012
1500602	PA	ALTAMIRA	2008	Ordinance n 28/2008		
5101407	MT	ARIPUANÃ	2008	Ordinance n 28/2008		
1501725	PA	BRASIL NOVO	2008	Ordinance n 28/2008	2013	Ordinance n 412/2013
5101902	MT	BRASNORTE	2008	Ordinance n 28/2008	2013	Ordinance n 412/2013
5103254	MT	COLNIZA	2008	Ordinance n 28/2008		
5103353	MT	CONFRESA	2008	Ordinance n 28/2008		
5103379	MT	COTRIGUAÇU	2008	Ordinance n 28/2008		
1502764	PA	CUMARU DO NORTE	2008	Ordinance n 28/2008		
1502939	PA	DOM ELISEU	2008	Ordinance n 28/2008	2012	Ordinance n 324/2012
5103858	MT	GAÚCHA DO NORTE	2008	Ordinance n 28/2008		
5105150	MT	JUÍNA	2008	Ordinance n 28/2008		
1302405	AM	LÁBREA	2008	Ordinance n 28/2008		
1100130	RO	MACHADINHO D'OESTE	2008	Ordinance n 28/2008		
5105580	MT	MARCELÂNDIA	2008	Ordinance n 28/2008	2013	Ordinance n 412/2013
5106158	MT	NOVA BANDEIRANTES	2008	Ordinance n 28/2008		
1100338	RO	NOVA MAMORÉ	2008	Ordinance n 28/2008		
5108907	MT	NOVA MARINGÁ	2008	Ordinance n 28/2008		
5106240	MT	NOVA UBIRATÃ	2008	Ordinance n 28/2008		
1505031	PA	NOVO PROGRESSO	2008	Ordinance n 28/2008		
1505064	PA	NOVO REPARTIMENTO	2008	Ordinance n 28/2008		
1505502	PA	PARAGOMINAS	2008	Ordinance n 28/2008	2010	Ordinance n 67/2010
5106299	MT	PARANAÍTA	2008	Ordinance n 28/2008		
5106422	MT	PEIXOTO DE AZEVEDO	2008	Ordinance n 28/2008		
1100189	RO	PIMENTA BUENO	2008	Ordinance n 28/2008		
5106802	MT	PORTO DOS GAÚCHOS	2008	Ordinance n 28/2008		
1100205	RO	PORTO VELHO	2008	Ordinance n 28/2008		
5107065	MT	QUERÊNCIA	2008	Ordinance n 28/2008	2011	Ordinance n 139/2011
1506187	PA	RONDON DO PARÁ	2008	Ordinance n 28/2008		
1506583	PA	SANTA MARIA DAS BARREIRAS	2008	Ordinance n 28/2008		
1506708	PA	SANTANA DO ARAGUAIA	2008	Ordinance n 28/2008	2012	Ordinance n 187/2012
5107859	MT	SÃO FÉLIX DO ARAGUAIA	2008	Ordinance n 28/2008		
1507300	PA	SÃO FÉLIX DO XINGU	2008	Ordinance n 28/2008		
1508126	PA	ULIANÓPOLIS	2008	Ordinance n 28/2008	2012	Ordinance n 324/2012
5108600	MT	VILA RICA	2008	Ordinance n 28/2008		
2100600	MA	AMARANTE DO MARANHÃO	2009	Ordinance n 102/2009		
5103700	MT	FELIZ NATAL	2009	Ordinance n 102/2009	2013	Ordinance n 412/2013
1503705	PA	ITUPIRANGA	2009	Ordinance n 102/2009		
5105101	MT	JUARA	2009	Ordinance n 102/2009		
1504208	PA	MARABÁ	2009	Ordinance n 102/2009		
1400308	RR	MUCAJAÍ	2009	Ordinance n 102/2009		
1505486	PA	PACAJÁ	2009	Ordinance n 102/2009		

IBGE Code	State	Municipality	In (year)	In (Legal Act)	Out (year)	Out (Legal Act)
1507953	PA	TAILÂNDIA	2009	Ordinance n 102/2009	2013	Ordinance n 412/2013
5100359	MT	ALTO BOA VISTA	2011	Ordinance n 175/2011		
1300706	AM	BOCA DO ACRE	2011	Ordinance n 175/2011		
5103056	MT	CLÁUDIA	2011	Ordinance n 175/2011		
2104800	MA	GRAJAÚ	2011	Ordinance n 175/2011		
1504703	PA	MOJU	2011	Ordinance n 175/2011		
5107248	MT	SANTA CARMEM	2011	Ordinance n 175/2011		
5108006	MT	TAPURAH	2011	Ordinance n 175/2011		
1500859	PA	ANAPU	2012	Ordinance n 323/2012		
1507805	PA	SENADOR JOSÉ PORFÍRIO	2012	Ordinance n 323/2012		

Source:MMA

9.4 Supplement material - Chapter 4

Table S 4.1 - Correlation matrix of the initial variables (correlations > 0.65 are highlighted, underlined and bold).

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Deforestation change (2004-2014) (km^2)	1																
2	Number of Fines (2004-2014)	-0.64	1															
3	Number of Embargoes (2005-2014)	**-0.73**	**0.87**	1														
4	Nonforest areas (km2)	0.21	-0.17	-0.15	1													
5	Agriculture credits 2014 (R$)*	-0.16	0.06	0.03	0.21	1												
6	Livestock credits 2014 (R$)*	-0.40	0.30	0.28	0.08	0.21	1											
7	Heads of cattle (2014)	**-0.66**	0.46	0.52	-0.07	0.03	**0.82**	1										
8	Soy (2014) (ton)	-0.26	0.05	0.05	0.17	**0.94**	0.20	0.04	1									
9	Logging in 2014 (R$)*	-0.20	0.30	0.28	-0.15	-0.03	0.03	0.09	-0.03	1								
10	Regular technical assistance	-0.16	0.08	0.04	0.17	0.45	0.26	0.16	0.45	-0.02	1							
11	GDP (2010)	-0.04	0.29	0.14	-0.04	0.06	0.06	0.03	0.03	0.06	0.03	1						
12	GDP per capita (2010)	-0.04	0.13	0.03	0.08	0.30	0.15	0.07	0.24	-0.02	0.18	0.35	1					
13	GDP agriculture (2010)	-0.32	0.28	0.26	0.00	**0.66**	0.30	0.30	0.58	0.23	0.30	0.16	0.21	1				
14	Companies (2014) (N)	-0.08	0.41	0.22	-0.01	0.14	0.13	0.09	0.08	0.08	0.08	**0.86**	0.56	0.19	1			
15	Population density (2010)	0.05	0.07	-0.01	-0.09	-0.03	-0.08	-0.08	-0.04	-0.03	-0.03	0.32	0.27	-0.04	0.43	1		
16	Non-native population (2010)	-0.32	0.18	0.15	0.02	0.26	0.38	0.34	0.31	-0.09	0.38	0.01	0.12	0.12	0.03	-0.01	1	
17	Gini index (2010)	0.01	0.04	0.05	-0.09	-0.15	-0.16	-0.06	-0.17	0.09	-0.25	0.04	-0.06	-0.04	0.03	-0.05	-0.42	1
18	Land value (2006) (R$ x 1,000)*	-0.52	0.36	0.36	-0.01	0.26	**0.79**	**0.83**	0.25	0.08	0.30	0.07	0.15	0.44	0.14	-0.08	0.38	-0.10
19	Roads (km)	-0.62	0.44	0.45	0.12	0.35	**0.65**	**0.71**	0.38	0.18	0.29	0.10	0.16	0.52	0.15	-0.09	0.27	0.00
20	Roads junctions (n)	-0.54	0.40	0.38	0.06	0.33	0.57	0.62	0.36	0.17	0.25	0.16	0.18	0.52	0.21	-0.05	0.24	-0.03
21	Settlements (2014) (km2)	-0.23	0.27	0.31	-0.21	-0.05	0.09	0.23	-0.05	0.26	-0.09	0.03	-0.04	0.20	0.03	-0.06	-0.05	0.20
22	Strict Preservation Protected Areas (km^2)	-0.17	0.24	0.31	-0.10	-0.04	-0.04	0.11	-0.05	0.07	-0.05	0.03	-0.02	0.08	0.03	-0.04	-0.08	0.17
23	Sustainable use Protected areas (km^2)	-0.10	0.20	0.28	-0.15	-0.06	-0.09	0.03	-0.06	0.13	-0.08	0.03	-0.03	0.09	0.01	-0.04	-0.19	0.23
24	Indigenous Lands (km^2)	-0.23	0.19	0.25	-0.11	-0.01	0.01	0.17	-0.01	0.03	-0.01	0.00	-0.01	0.06	0.00	-0.04	-0.11	0.28
25	CAR share	-0.14	0.02	0.02	0.18	0.24	0.40	0.29	0.24	-0.03	0.31	-0.05	0.08	0.18	-0.01	-0.14	0.55	-0.37
26	CAR (km2)	-0.53	0.43	0.52	-0.08	0.19	0.37	0.50	0.23	0.25	0.16	0.04	0.06	0.36	0.07	-0.10	0.03	0.16
27	CAR - small properties (km^2)	-0.50	0.52	0.56	-0.22	0.01	0.35	0.54	0.02	0.36	-0.04	0.04	0.00	0.36	0.08	-0.09	0.11	0.16
28	CAR - medium properties (km^2)	-0.52	0.45	0.53	0.01	0.23	0.35	0.49	0.26	0.14	0.13	0.08	0.07	0.33	0.10	-0.08	0.09	0.12
29	CAR - large properties (km^2)	-0.41	0.30	0.38	-0.05	0.18	0.28	0.37	0.21	0.21	0.17	0.02	0.05	0.29	0.04	-0.08	-0.04	0.14
30	Fires (number of hotspots)	**-0.81**	0.59	**0.73**	-0.01	0.12	0.40	**0.68**	0.18	0.22	0.11	0.03	0.02	0.35	0.08	-0.08	0.14	0.12
31	Rainfall (mm/year)	-0.07	0.08	0.08	-0.44	-0.09	-0.19	-0.10	-0.07	0.16	-0.14	0.04	-0.09	0.02	0.00	0.05	-0.17	0.20
32	Average temperature (^{o}C)	0.16	-0.12	-0.09	-0.21	-0.34	-0.39	-0.32	-0.32	0.08	-0.35	0.03	-0.15	-0.24	-0.02	0.13	-0.46	0.20
33	Maximum temp (^{o}C)**	0.20	-0.16	-0.12	-0.11	-0.30	-0.37	-0.33	-0.28	0.05	-0.32	0.02	-0.12	-0.23	-0.01	0.11	-0.47	0.15
34	Priority municipalities	**-0.66**	0.47	0.47	-0.15	0.09	0.26	0.39	0.18	0.18	0.13	0.01	0.01	0.20	0.03	-0.04	0.20	0.04

35	Municipality area (km²)	-0.33	0.35	0.43	-0.14	0.02	0.08	0.26	0.03	0.17	-0.01	0.03	0.00	0.19	0.04	-0.07	-0.14	0.32

	Variables	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
18	Land value (2006) (R$ x 1,000)	1																	
19	Roads	**0.71**	1																
20	Roads junctions	0.63	**0.93**	1															
21	Settlements (2014) (km2)	0.16	0.20	0.16	1														
22	Strict Preservation Protected Areas (km2)	0.04	0.13	0.07	0.22	1													
23	Sustainable use Protected areas (km2)	-0.02	0.04	0.01	0.32	**0.73**	1												
24	Indigenous Lands (km2)	0.10	0.17	0.11	0.16	0.52	0.37	1											
25	CAR share	0.36	0.24	0.22	0.04	-0.24	-0.17	-0.28	1										
26	CAR (km2)	0.47	0.58	0.48	0.53	0.39	0.59	0.29	0.15	1									
27	CAR - small properties (km2)	0.44	0.47	0.38	**0.74**	0.27	0.28	0.20	0.15	0.58	1								
28	CAR - medium properties (km2)	0.43	0.57	0.48	0.44	0.29	0.28	0.28	0.13	**0.66**	0.47	1							
29	CAR - large properties (km2)	0.37	0.47	0.39	0.38	0.38	0.64	0.27	0.11	**0.95**	0.38	0.48	1						
30	Fires (number of hotspots)	0.52	**0.70**	0.57	0.33	0.26	0.18	0.30	0.06	0.62	0.58	0.59	0.49	1					
31	Rainfall (mm/year)	-0.10	-0.13	-0.08	0.19	0.18	0.23	0.20	-0.26	0.14	0.13	0.03	0.13	-0.04	1				
32	Average temperature (oC)	-0.37	-0.32	-0.31	0.05	0.00	0.03	-0.06	-0.37	-0.16	-0.07	-0.19	-0.14	-0.15	0.21	1			
33	Maximum temp (oC)**	-0.37	-0.30	-0.30	0.02	-0.02	0.01	-0.10	-0.34	-0.18	-0.11	-0.20	-0.14	-0.16	0.09	**0.97**	1		
34	Priority municipalities	0.34	0.42	0.35	0.15	0.05	0.04	0.11	0.13	0.38	0.35	0.31	0.31	0.50	0.04	-0.08	-0.11	1	
35	Municipality area (km2)	0.19	0.32	0.23	0.37	**0.78**	**0.74**	**0.79**	-0.24	**0.67**	0.40	0.49	0.64	0.44	0.28	-0.05	-0.09	0.19	1

* Values deflated to Jun/2016 in Brazilian Reais (R$) using the General Prices Index (IGP-M, brazilian acronym)

** In the hottest quarter of the year (June/July/August)

Table S 4.2 - Results of the OLS regression model

Source	SS	df	MS			
Model	3039577.28	15	202638.485	Number of obs	=	760
Residual	1281739.74	744	1722.76847	F(15, 744)	=	117.62
				Prob > F	=	0.0000
				R-squared	=	0.7034
				Adj R-squared	=	0.6974
Total	4321317.02	759	5693.43481	Root MSE	=	41.506

Deforestation change 2004-2014	Coef.	Std. Err.	t	P>t
Number of Fines (2004-2014)	-0.096	0.008	-11.42	0.000
Priority Municipalities	-71.670	5.736	-12.49	0.000
Non-forest area share	23.696	4.663	5.08	0.000
Agriculture loans value 2004-2014	0.000	0.004	-0.09	0.925
Livestock loans value 2004-2014	0.013	0.016	0.78	0.433
In-migrants in 2010	-0.545	0.086	-6.34	0.000
Roands/Highways junctions (km)	-0.225	0.039	-5.81	0.000
GDP per capita	0.053	0.019	2.78	0.006
CAR	-0.006	0.001	-8.53	0.000
Settlements area 2014	0.005	0.002	3.30	0.001
Strict Preservation PA 2014	-0.002	0.001	-2.65	0.008
Sustainable Use PA 2014	0.006	0.001	5.92	0.000
Indigenous Lands 2014	-0.001	0.000	-3.36	0.001
Rainfall (mm/year)	0.000	0.004	0.11	0.913
Average Temp hottest Quarter (Jun-Aug) (oC)	-4.005	1.775	-2.26	0.024
_cons	128.365	50.434	2.55	0.011

Table S 4.3 - Deforestation SAC model results.

```
Spatial autoregressive model                Number of obs     =        760
GS2SLS estimates                            Wald chi2(16)     =     285.80
                                            Prob > chi2       =     0.0000
                                            Pseudo R2         =     0.1574
```

Deforestation change 2004-2014	Coef.	Std. Err.	z	P>z
Number of Fines (2004-2014)	-0.095	0.025	-3.85	0.000
Priority Municipalities	-62.366	13.693	-4.55	0.000
Non-forest area share	26.159	6.859	3.81	0.000
Agriculture loans value 2004-2014	0.004	0.007	0.56	0.576
Livestock loans value 2004-2014	0.011	0.026	0.44	0.658
In-migrants in 2010	-0.316	0.102	-3.08	0.002
Roands/Highways junctions (km)	-0.201	0.085	-2.36	0.018
GDP per capita	0.047	0.022	2.12	0.034
CAR	-0.006	0.002	-2.71	0.007
Settlements area 2014	0.006	0.002	2.90	0.004
Strict Preservation PA 2014	-0.002	0.001	-2.04	0.041
Sustainable Use PA 2014	0.006	0.003	2.26	0.024
Indigenous Lands 2014	-0.001	0.001	-1.14	0.254
Rainfall (mm/year)	0.002	0.008	0.23	0.819
Average Temp hottest Quarter (Jun-Aug) (oC)	-2.081	3.311	-0.63	0.530
_cons	101.447	92.286	1.10	0.272
Wdef				
deforestation change 2004-2014	1.662	0.460	3.61	0
e.deforestation change 2004-2014	2.117	0.224	9.44	0
Wald test of spatial terms: chi2(2) = 113.69	Prob > chi2 = 0.0000			

Table S 4.4 - Amazon and Cerrado annual deforestation rates (km2,) and annual percentage of forest loss. (Source: INPE)

Year	Deforestation rates (km2)		Biome percentage deforested	
	Amazon*	Cerrado**	Amazon	Cerrado
2002	21,651	27,663	0.52%	1.36%
2003	25,396	26,489	0.61%	1.30%
2004	27,772	26,489	0.66%	1.30%
2005	19,014	15,837	0.45%	0.78%
2006	14,286	15,837	0.34%	0.78%
2007	11,651	13,272	0.28%	0.65%
2008	12,911	13,272	0.31%	0.65%
2009	7,464	8,765	0.18%	0.43%
2010	7,000	8,765	0.17%	0.43%
2011	6,418	8,710	0.15%	0.43%
2012	4,571	8,710	0.11%	0.43%
2013	5,891	11,778	0.14%	0.58%
2014	5,012	9,003	0.12%	0.44%
2015	6,207	10,064	0.15%	0.49%
2016	7,893	5,960	0.19%	0.29%
2017	6,947	6,397	0.17%	0.31%
Biomes total area (km2)***			4,196,943	2,036,448

* Prodes Amazonia: http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes (accessed on 24 Sep 2018).
** Prodes Cerrado: http://www.obt.inpe.br/OBT/noticias/inpe-divulga-dados-sobre-o-desmatamento-do-bioma-cerrado (accessed on 24 Sep 2018).
*** Source (IBGE, 2010) https://ww2.ibge.gov.br/home/presidencia/noticias/21052004biomashtml.shtm) (accessed on 06 Nov 2016).

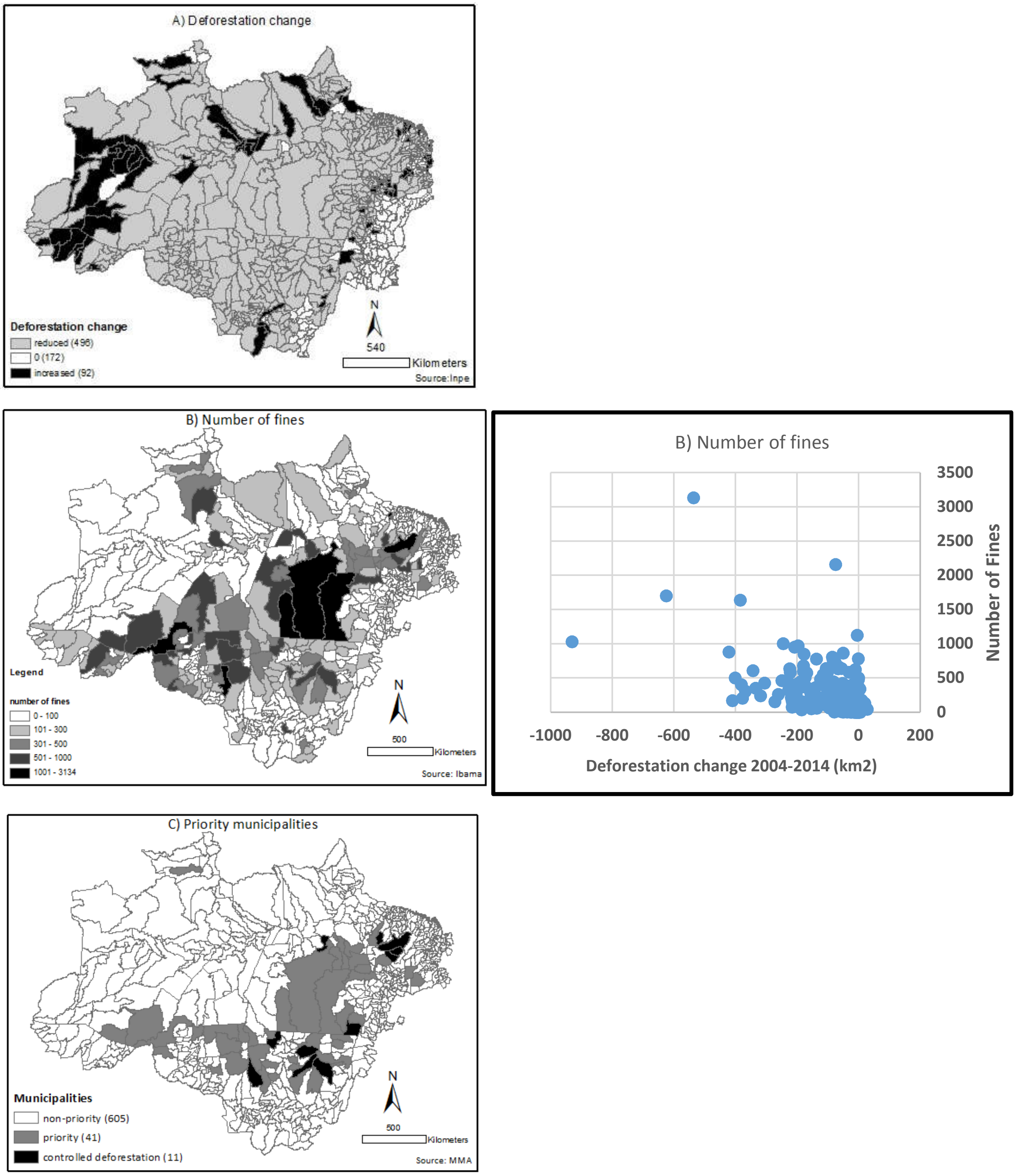

Figure S 4.1 - Selected variables/covariates distributed by the 760 municipalities (spatial and scatterplot) for the spatial cross-section analysis: A) deforestation change 2004-2014; B) number of fines; C) priority municipalities; D) non-forest area; E) public loans for agriculture; F) public loans for livestock; G) in-migrants population; H) roads/highways junctions; I) GDP per capita; J) CAR; K) settlements; L) strict preservation protected areas; M) sustainable use protected areas; N) indigenous lands; O) annual rainfall; and P) maximum temperature of the hottest quarter (jun-jul-aug).

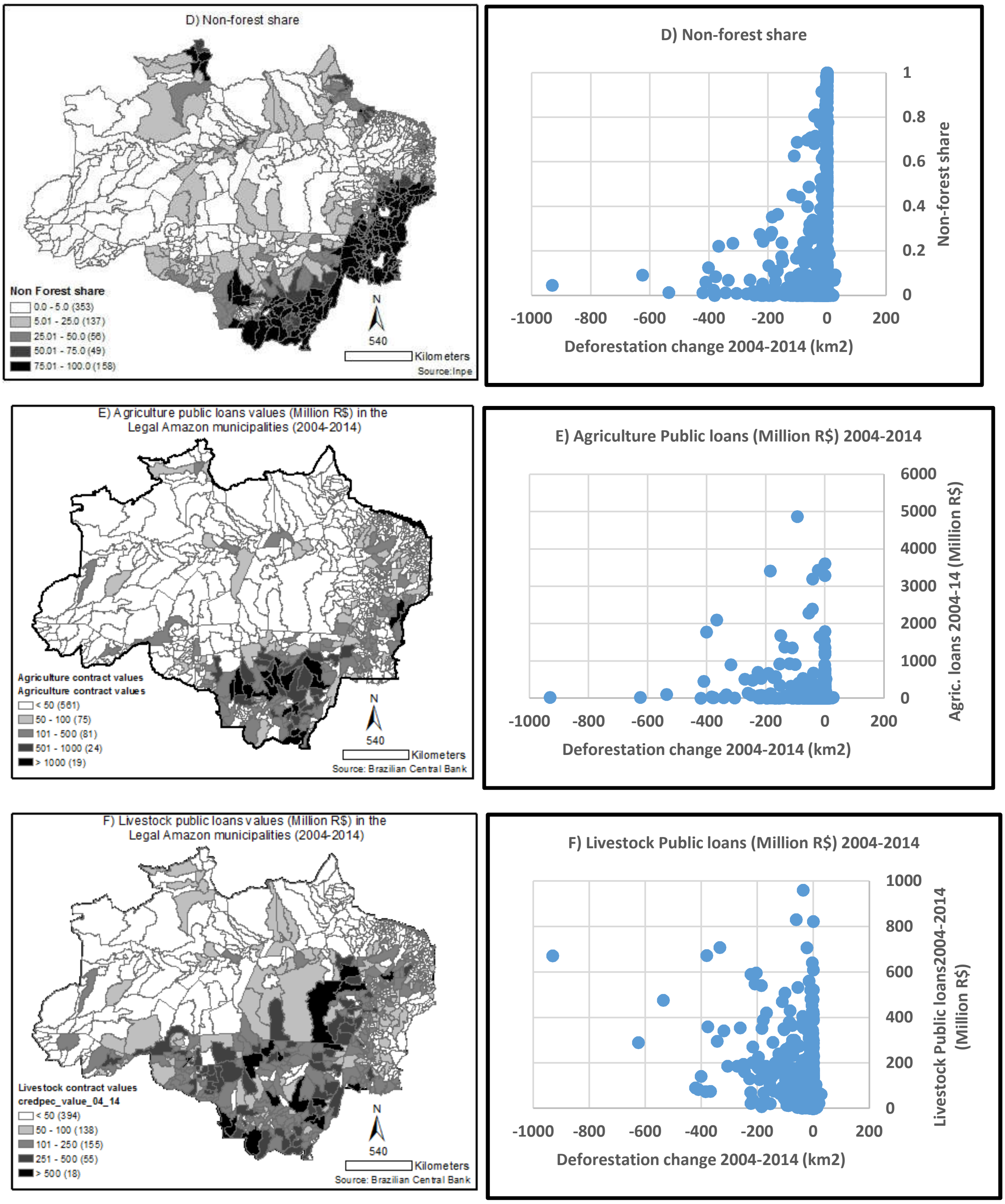

Figure S 4.1 (cont.)- Selected variables/covariates distributed by the 760 municipalities for the spatial cross-section analysis: A) deforestation change 2004-2014; B) number of fines; C) priority municipalities; D) non-forest area; E) public loans for agriculture; F) public loans for livestock; G) in-migrants population; H) roads/highways junctions; I) GDP per capita; J) CAR; K) settlements; L) strict preservation protected areas; M) sustainable use protected areas; N) indigenous lands; O) annual rainfall; and P) maximum temperature of the hottest quarter (jun-jul-aug).

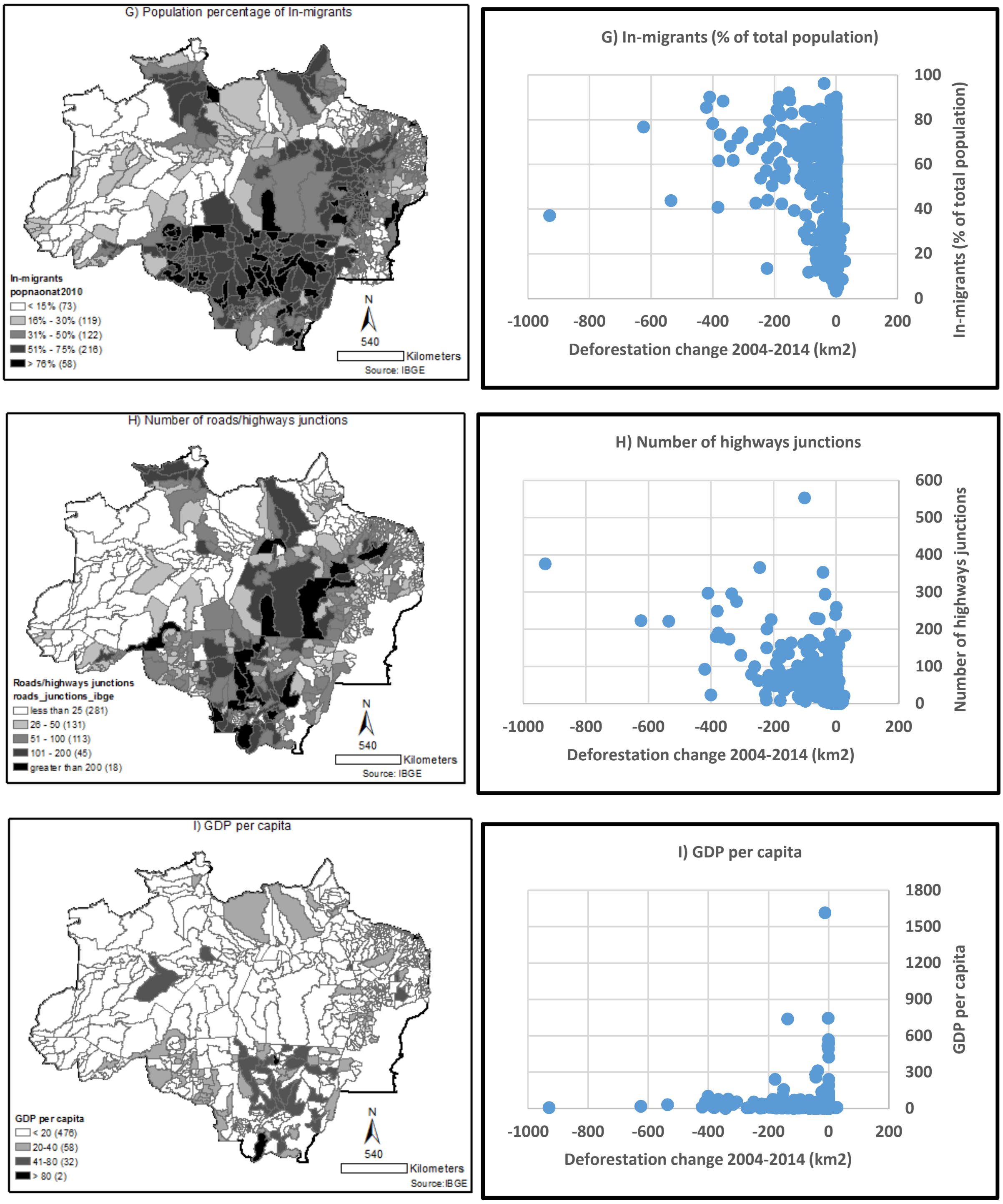

Figure S 4.1 (cont.)- Selected variables/covariates distributed by the 760 municipalities (spatial and scatterplot) for the spatial cross-section analysis: A) deforestation change 2004-2014; B) number of fines; C) priority municipalities; D) non-forest area; E) public loans for agriculture; F) public loans for livestock; G) in-migrants population; H) roads/highways junctions; I) GDP per capita; J) CAR; K) settlements; L) strict preservation protected areas; M) sustainable use protected areas; N) indigenous lands; O) annual rainfall; and P) maximum temperature of the hottest quarter (jun-jul-aug).

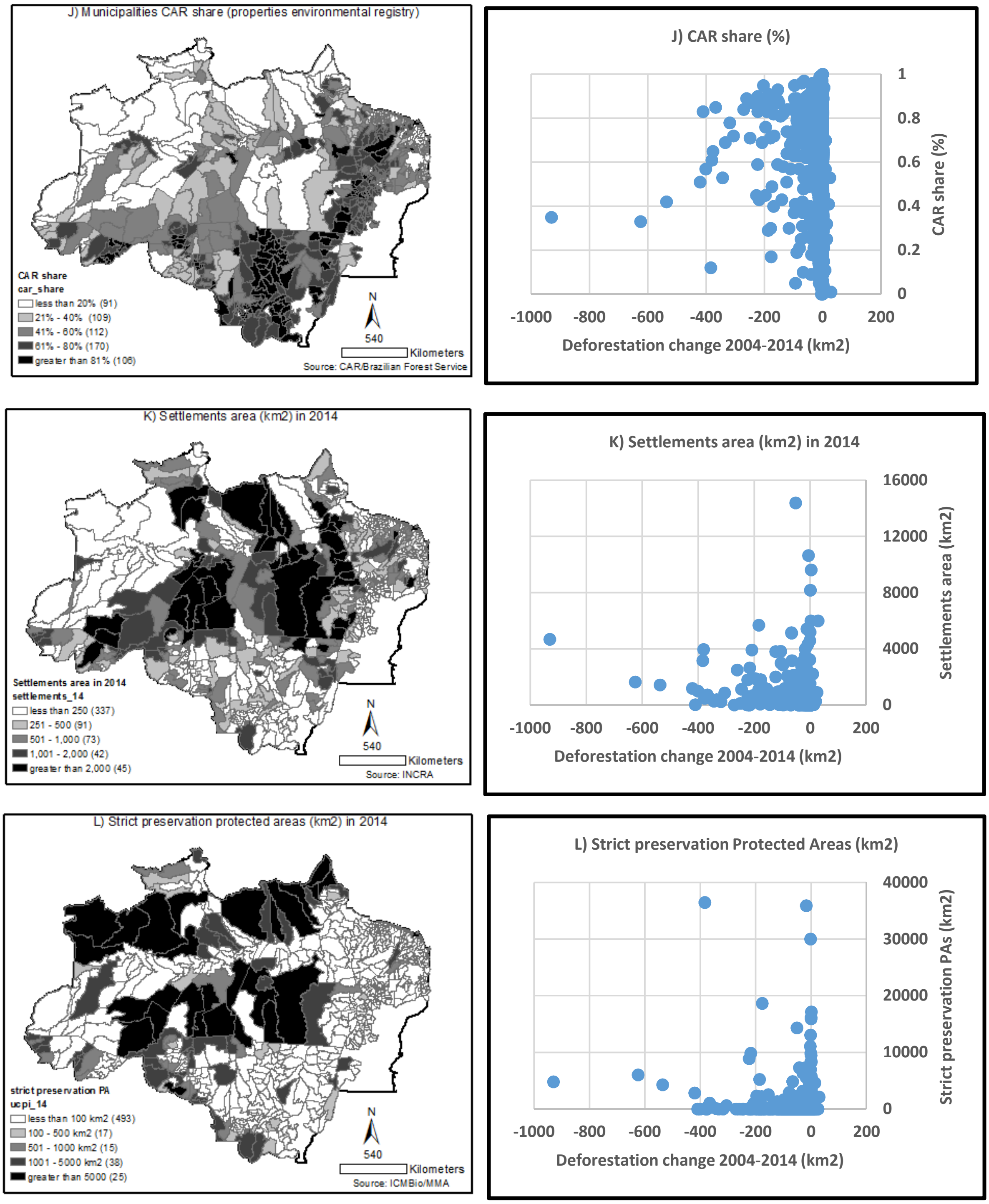

Figure S 4.1 (cont.) Selected variables/covariates distributed by the 760 municipalities (spatial and scatterplot) *for the spatial cross-section analysis: A) deforestation change 2004-2014; B) number of fines; C) priority municipalities; D) non-forest area; E) public loans for agriculture; F) public loans for livestock; G) in-migrants population; H) roads/highways junctions; I) GDP per capita; J) CAR share; K) settlements; L) strict preservation protected areas; M) sustainable use protected areas; N) indigenous lands; O) annual rainfall; and P) maximum temperature of the hottest quarter (jun-jul-aug).*

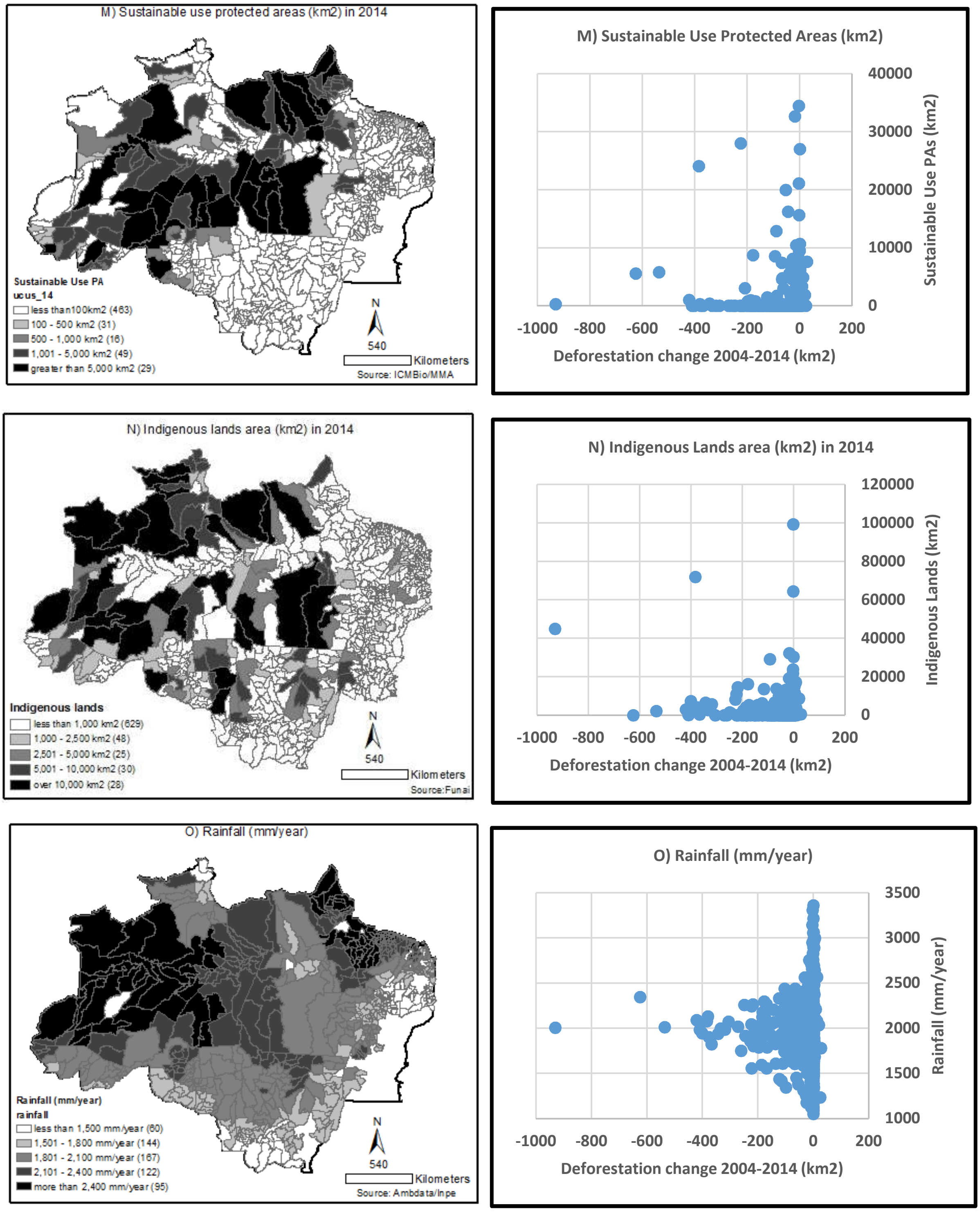

Figure 4.1 S (cont.) Selected variables/covariates distributed by the 760 municipalities (spatial and scatterplot) for the spatial cross-section analysis: A) deforestation change 2004-2014; B) number of fines; C) priority municipalities; D) non-forest area; E) public loans for agriculture; F) public loans for livestock; G) in-migrants population; H) roads/highways junctions; I) GDP per capita; J) CAR share; K) settlements; L) strict preservation protected areas; M) sustainable use protected areas; N) indigenous lands; O) annual rainfall; and P) maximum temperature of the hottest quarter (jun-jul-aug).

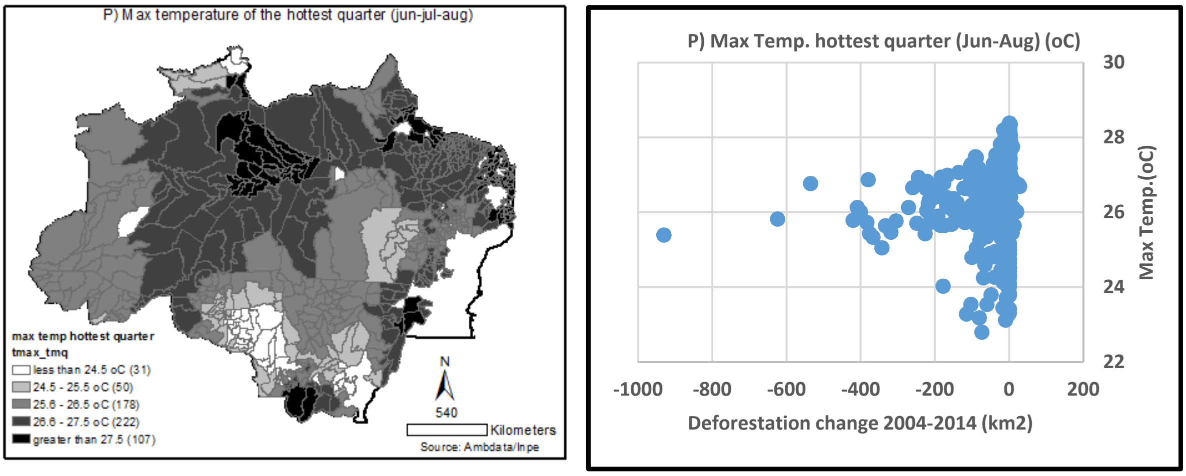

Figure 4.1 S (cont.) Selected variables/covariates distributed by the 760 municipalities (spatial and scatterplot) for the spatial cross-section analysis: A) deforestation change 2004-2014; B) number of fines; C) priority municipalities; D) non-forest area; E) public loans for agriculture; F) public loans for livestock; G) in-migrants population; H) roads/highways junctions; I) GDP per capita; J) CAR share; K) settlements; L) strict preservation protected areas; M) sustainable use protected areas; N) indigenous lands; O) annual rainfall; and P) maximum temperature of the hottest quarter (jun-jul-aug).

9.5 Supplement material – Chapter 5

Table S 5.1 – Initial group of pre-policy variables for correlation check.

Outcomes
Deforestation
Pastureland
Annual agriculture
Natural regeneration
Pre-policy variables
Municipality area (tousand km2)
Population density (2007)
Fines (2002-2005)
Deforestation rate per municipality area (2002-2004)
Fines(N) per deforested area (km2) (2003-2005)
Agricultural loans 2004 (cattle and agriculture) (Million R$)
Tractors per farm (2006)
Soy price (2005)
Total GDP 2004 (Million R$)
Forest share 2004 (TerraClass)
Non-forest area share 2004
Strict Preservation Protected Areas share (2004)
Sustainable use Protected areas share (2004)
Indigenous Lands share (2004)
Settlements share (2004)
Rainfall (mm)
Temperature (max) for the hottest quarter
Roads/Highways density
Number of roads/highways junctions

Table S 5.2 - Correlation matrix of the initial variables.

	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Municipality area (tousand km2)	1.00																	
2	Population density (2007)	-0.08	1.00																
3	Fines 2002	0.17	0.09	1.00															
4	Fines 2003	0.12	0.30	**0.65**	1.00														
5	Fines 2004	0.15	0.08	**0.69**	**0.66**	1.00													
6	Fines 2005	0.19	0.10	**0.65**	**0.65**	**0.77**	1.00												
7	Deforestation rate per municipality area (2002)	-0.17	0.21	0.10	0.03	0.05	0.03	1.00											
8	Deforestation rate per municipality area (2003)	-0.16	0.01	0.05	0.02	0.04	0.01	0.19	1.00										
9	Deforestation rate per municipality area (2004)	-0.16	0.02	0.21	0.10	0.21	0.18	0.46	0.39	1.00									
10	Deforestation rate per municipality area (2005)	-0.19	-0.02	0.09	0.01	0.09	0.07	0.40	0.36	**0.66**	1.00								
11	2003 Fines(N) per deforested area (km2)	-0.03	0.17	0.12	0.25	0.09	0.09	-0.09	-0.07	-0.08	-0.09	1.00							
12	2004 Fines(N) per deforested area (km2)	-0.03	0.19	0.10	0.28	0.16	0.12	-0.08	-0.11	-0.15	-0.14	0.33	1.00						
13	2005 Fines(N) per deforested area (km2)	-0.01	0.48	0.25	**0.65**	0.28	0.30	-0.08	-0.07	-0.11	-0.14	0.43	0.43	1					
14	Agricultural loans 2004* (cattle and agriculture) (Million R$)	0.03	-0.03	0.24	0.18	0.21	0.18	0.05	0.05	0.18	0.03	-0.02	-0.05	-0.04	1				
15	Agriculture loans 2004* (Million R$)	0.01	-0.03	0.14	0.14	0.13	0.09	0.04	0.05	0.15	0.00	-0.02	-0.04	-0.03	**0.97**	1			
16	Livestock loans 2004* (Million R$)	0.07	-0.04	0.46	0.23	0.38	0.38	0.05	0.02	0.17	0.13	-0.01	-0.05	-0.03	0.32	0.09	1		
17	Tractors per farm (2006)	0.00	-0.04	0.03	0.02	0.02	0.02	-0.01	0.02	0.09	0.00	-0.03	-0.02	-0.04	**0.65**	**0.68**	0.04	1	
18	Soy price (2005)	0.02	-0.07	0.21	0.10	0.16	0.17	0.03	0.01	0.14	0.07	-0.06	-0.09	-0.08	0.41	0.37	0.24	0.36	1
19	Total GDP 2004 (Million R$)	0.02	0.31	0.31	0.47	0.32	0.31	0.03	-0.03	-0.02	-0.05	0.13	0.19	0.56	0.08	0.06	0.11	0.03	0.01
20	Forest share 2004 (TerraClass)	0.51	-0.06	0.11	0.07	0.17	0.17	-0.13	-0.11	-0.08	-0.14	-0.02	0.01	0.01	-0.13	-0.11	-0.11	-0.15	-0.16
21	Non-forest area share 2004	-0.05	-0.08	-0.08	-0.07	-0.08	-0.07	-0.17	-0.17	-0.21	-0.14	0.03	0.11	-0.02	0.26	0.28	-0.01	0.37	0.33
22	Strict Preservation Protected Areas share (2004)	0.14	-0.04	0.01	0.00	0.09	0.09	-0.10	-0.11	-0.09	-0.11	0.01	-0.02	0.07	-0.05	-0.05	-0.03	-0.05	-0.05
23	Sustainable Use Protected areas share (2004)	0.12	-0.05	0.01	0.04	0.03	0.05	-0.12	-0.09	-0.13	-0.14	-0.02	-0.04	-0.03	-0.08	-0.07	-0.05	-0.09	-0.07
24	Indigenous Lands share (2004)	0.37	-0.08	0.07	0.03	0.15	0.11	-0.13	-0.15	-0.11	-0.14	-0.02	-0.03	-0.03	0.05	0.04	0.08	0.09	0.04
25	Settlements share (2004)	-0.06	-0.04	-0.09	-0.06	-0.04	-0.07	-0.02	0.07	0.00	0.02	-0.06	0.00	-0.05	-0.04	-0.03	-0.03	0.02	0.04
26	Rainfall	-0.03	-0.02	0.01	-0.05	-0.03	-0.07	0.07	-0.07	0.01	0.01	-0.04	-0.10	-0.06	0.09	0.09	0.00	0.14	0.11
27	Temperature (max)**	-0.07	0.11	-0.16	-0.06	-0.25	-0.12	0.03	-0.01	-0.13	-0.13	0.08	0.12	0.13	-0.27	-0.20	-0.35	-0.24	-0.26
28	Roads/highways density	-0.44	0.12	-0.09	-0.08	-0.14	-0.14	0.32	0.29	0.28	0.27	-0.08	-0.13	-0.08	0.07	0.05	0.08	0.06	0.06
29	Number of roads/highways junctions	0.19	-0.06	0.38	0.22	0.29	0.36	0.06	0.08	0.24	0.12	-0.07	-0.09	-0.05	0.41	0.31	0.50	0.25	0.39

* Values deflated to Jun/2016 in Brazilian Reais (R$) using the General Prices Index (IGP-M, brazilian acronym)

** In the hottest quarter of the year (June/July/August)

Table S 5.2 (cont.) - Correlation matrix of the initial variables.

	Variable	19	20	21	22	23	24	25	26	27	28	29
19	Total GDP 2004 (Million R$)	1										
20	Forest share 2004 (TerraClass)	0.02	1									
21	Non-forest area share 2004	-0.04	-0.35	1								
22	Strict Preservation Protected Areas share (2004)	0.04	0.22	0.11	1							
23	Sustainable Use Protected areas share (2004)	-0.01	0.34	-0.12	0.02	1						
24	Indigenous Lands share (2004)	-0.03	0.31	0.10	0.14	-0.03	1					
25	Settlements share (2004)	-0.05	-0.05	-0.02	0.13	0.10	-0.04	1				
26	Rainfall	-0.03	-0.04	0.03	-0.08	-0.06	-0.01	-0.09	1			
27	Temperature (max) for the hottest quarter	0.06	0.00	-0.07	-0.10	0.04	-0.30	-0.06	-0.08	1		
28	Roads/highways density	-0.01	**-0.66**	-0.05	-0.25	-0.27	-0.33	0.08	-0.01	-0.06	1	
29	Number of roads/highways junctions	0.15	-0.01	0.13	-0.06	-0.07	0.09	-0.04	0.01	-0.29	0.16	1

Table S 5.3 - Gini Index for land tenure results.

Paired t test

Variable	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
fund_~06	769	.7168656	.0048194	.1336461	.7074049	.7263264
fund_~17	769	.6963688	.004396	.1219058	.6877392	.7049985
diff	769	.0204968	.004049	.112282	.0125484	.0284452

```
    mean(diff) = mean(fund_gini_06 - fund_gini_17)              t =   5.0622
Ho: mean(diff) = 0                               degrees of freedom =      768

Ha: mean(diff) < 0           Ha: mean(diff) != 0           Ha: mean(diff) > 0
Pr(T < t) = 1.0000         Pr(|T| > |t|) = 0.0000          Pr(T > t) = 0.0000
```

The Gini Index for land tenure[41]was estimated by using all the 17 categories of farm size presented in the Agricultural Census for 2006 and 2017 (IBGE, 2009; IBGE, 2018), in which total farms and total area for each category of farm size, for each municipality, were included**.**

This is a test for paired means, i.e. the means are not randomly distributed, but always refer to the same municipality before and after.

Here, the Gini Index for land tenure results, comparing before (Census 2006) and after 2008 (Census 2017) do not reject the null hypothesis: land tenure has not changed. Therefore, although CAR is recent, there is evidence that the phenomena analyzed for small private properties and medium-large should not have changed.

[41] Procedure developed in partnership with PhD Rafael Feltran Barbieri, currently a Natural Infrastructure and Land Use Economist at WRI Brazil.

9.6 Supplement material – Chapter 6

Table S 6.1 - Basic statistics of the initial group of variables.

Variable description	Variable abreviation	Obs	Mean	Std. Dev.	Min	Max
Natural regeneration persistent (km2)	secveg_per	657	63.1	91.7	0.0	728.0
Number of Fines (2004-2014)	ai_n_04_14	657	107.2	240.1	0.0	3,134.0
Embargoes (2005-2014)	emb_05_14	657	29.4	77.0	0.0	1,157.0
CAR share (km2)	car_share	657	2,166.2	3,966.5	0.0	40,512.5
Agriculture persistence (km2)	agr_pers	657	23.5	159.0	0.0	2,977.9
Clean pasture persistence (km2)	c_pers	657	218.1	384.0	0.0	2,846.5
Agriculture credits 2014 (R$)*	credagr_v~14	657	115.5	424.3	0.0	4,868.9
Livestock credits 2014 (R$)*	credpec_v~14	657	97.8	136.1	0.0	960.0
Heads of cattle (2014)	cattle2014	657	116,213.3	174,931.3	20.0	2,213,310.0
Soy (2014) (ha)	soy2014	657	13,677.9	52,949.9	0.0	635,000.0
Regular technical assistence	regater	657	17.6	17.3	0.0	82.6
Roads (km)	roads_ibge	657	484.0	588.5	0.0	4,820.5
Roads junctions (n)	roads_junc~e	657	43.6	57.5	0.0	553.0
Land value (2006) (R$)*	landval~2006	657	127,606.9	170,046.9	0.0	1,424,228.0
Population density (2010)	popdens~2010	657	25.8	131.7	0.0	2,465.9
Rural population density (2010)	poprura~2010	657	7.0	19.9	0.0	320.6
Non-native population (2010)	popnaon~2010	657	43.6	22.8	3.3	96.4
Gini index (2010)	gini2010	657	0.6	0.1	0.4	0.8
Fires	fire04-14	657	1,748.2	3,073.3	1.0	44,734.0
Rainfall (mm/year)	rainfall	657	1,959.0	400.6	1,127.0	3,362.0
Average temperature (oC)	temp_med	657	25.9	1.1	22.2	27.5
Nonforest areas (km2)	nonforest	657	1,066.7	2,325.5	0.0	19,956.3
Municipality area (km2)	area_mun	657	7,240.0	14,562.7	66.3	159,533.3

* Values deflated to Jun/2016 in Brazilian Reais (R$) using the General Prices Index (IGP-M, brazilian acronym)

Table S 6.2 – Correlation matrix of the initial variables (correlations > 0.65 are underlined and bold).

	Initial variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	Secondary vegetation persistent (km2)	1																						
2	Number of Fines (2004-2014)	0.49	1																					
3	Embargoes (2005-2014)	0.46	**0.87**	1																				
4	CAR share (km2)	0.52	0.42	0.50	1																			
5	Agriculture persistence (km2)	0.12	0.09	0.07	-0.04	1																		
6	Clean pasture persistence (km2)	0.43	0.31	0.32	0.19	-0.01	1																	
7	Agriculture credits 2014 (R$)*	0.06	0.06	0.03	-0.06	0.62	0.00	1																
8	Livestock credits 2014 (R$)*	0.30	0.30	0.28	0.15	0.07	**0.73**	0.22	1															
9	Heads of cattle (2014)	0.47	0.45	0.51	0.36	-0.02	**0.80**	0.04	**0.82**	1														
10	Soy (2014) (ha)	0.10	0.05	0.05	-0.07	**0.71**	0.03	**0.94**	0.21	0.04	1													
11	Regular technical assistence	0.08	0.08	0.04	-0.01	0.30	0.17	0.45	0.28	0.18	0.46	1												
12	Roads (km)	0.52	0.45	0.46	0.32	0.18	0.51	0.34	**0.67**	**0.73**	0.38	0.30	1											
13	Roads junctions (n)	0.48	0.40	0.38	0.25	0.15	0.46	0.32	0.58	0.63	0.36	0.27	**0.94**	1										
14	Land value (2006) (R$)*	0.45	0.35	0.35	0.27	0.12	**0.73**	0.26	**0.80**	**0.83**	0.25	0.31	**0.73**	0.63	1									
15	Population density (2010)	-0.09	0.05	-0.01	-0.08	-0.02	-0.08	-0.03	-0.08	-0.09	-0.04	-0.04	-0.09	-0.06	-0.09	1								
16	Rural population density (2010)	-0.14	-0.09	-0.09	-0.14	-0.05	-0.14	-0.08	-0.16	-0.15	-0.08	-0.08	-0.16	-0.11	-0.16	0.37	1							
17	Non-native population (2010)	0.05	0.18	0.15	-0.12	0.22	0.42	0.28	0.40	0.35	0.33	0.41	0.31	0.27	0.38	-0.02	-0.11	1						
18	Gini index (2010)	0.16	0.04	0.05	0.27	-0.11	-0.11	-0.17	-0.17	-0.07	-0.19	-0.27	-0.04	-0.06	-0.12	-0.05	-0.08	-0.42	1					
19	Fires	0.57	0.62	**0.75**	0.50	0.11	0.43	0.10	0.42	**0.70**	0.17	0.12	**0.69**	0.56	0.54	-0.09	-0.14	0.19	0.07	1				
20	Rainfall (mm/year)	0.13	0.05	0.05	0.18	-0.03	-0.13	-0.08	-0.26	-0.17	-0.07	-0.16	-0.15	-0.10	-0.16	0.04	-0.01	-0.25	0.25	-0.04	1			
21	Average temperature (oC)	-0.07	-0.15	-0.11	-0.02	-0.13	-0.37	-0.35	-0.44	-0.36	-0.33	-0.37	-0.34	-0.34	-0.41	0.13	0.23	-0.51	0.20	-0.17	0.21	1		
22	Nonforest areas (km2)	0.02	0.05	0.06	0.15	0.08	0.03	0.34	0.38	0.27	0.34	0.27	0.53	0.42	0.33	-0.07	-0.14	0.06	0.03	0.27	-0.17	-0.218	1	
23	Municipality area (km2)	0.44	0.34	0.42	**0.67**	0.01	0.10	0.02	0.07	0.24	0.03	-0.01	0.31	0.22	0.18	-0.08	-0.14	-0.15	0.34	0.44	0.26	-0.06	0.32	1

Table S 6.3 - Results of the OLS regression model

Source	SS	df	MS
Model	3011506.8	11	273773.345
Residual	2499031.61	645	3874.46761
Total	5510538.41	656	8400.21099

Number of obs	=	657
F(11, 645)	=	70.66
Prob > F	=	0.0000
R-squared	=	0.5465
Adj R-squared	=	0.5388
Root MSE	=	62.245

Secondary Vegetation Persistence	Coef.	Std. Err.	t	P>t
Number of Fines (2004-2014)	0.046	0.013	3.540	0.000
Non-forest area	-55.702	9.682	-5.750	0.000
Priority Municipalities	28.972	8.535	3.390	0.001
CAR area	0.006	0.001	8.100	0.000
Agriculture persistence	0.046	0.016	2.810	0.005
Clean Pasture persistence	0.045	0.009	5.260	0.000
Roads/Highways (km2)	0.050	0.006	8.370	0.000
In-migrants in 2010	-0.359	0.139	-2.580	0.010
Population Density in 2010	-0.032	0.019	-1.670	0.095
Rainfall (mm/year)	0.014	0.007	2.060	0.040
Average Temp (oC)	5.354	2.792	1.920	0.056
_cons	130.801	76.735	-1.700	0.089

Table S 6.4 - Natural regeneration persistence SAC model results.

```
Spatial autoregressive model                              Number of obs     =        657
GS2SLS estimates                                          Wald chi2(12)     =     335.19
                                                          Prob > chi2       =     0.0000
                                                          Pseudo R2         =     0.4394
```

Secondary Vegetation Persistence	Coef.	Std. Err.	z	P>z
Number of Fines (2004-2014)	0.043	0.016	2.73	0.006
Non-forest area	-64.690	9.252	-6.99	0.000
Priority Municipalities	28.205	14.095	2.00	0.045
CAR area	0.004	0.001	3.19	0.001
Agriculture persistence	0.039	0.029	1.33	0.183
Clean Pasture persistence	0.043	0.012	3.69	0.000
Roads/Highways (km2)	0.049	0.012	4.17	0.000
In-migrants in 2010	-0.795	0.174	-4.56	0.000
Population Density in 2010	0.000	0.009	-0.03	0.974
Rainfall (mm/year)	0.009	0.012	0.72	0.469
Average Temp (oC)	7.299	3.723	1.96	0.050
_cons	228.048	110.620	-2.06	0.039
W				
secveg_per	1.442	0.429	3.360	0.001
e.secveg_per	3.038	0.518	5.870	0.000
Wald test of spatial terms:	chi2(2) = 48.91	Prob > chi2 = 0.0000		

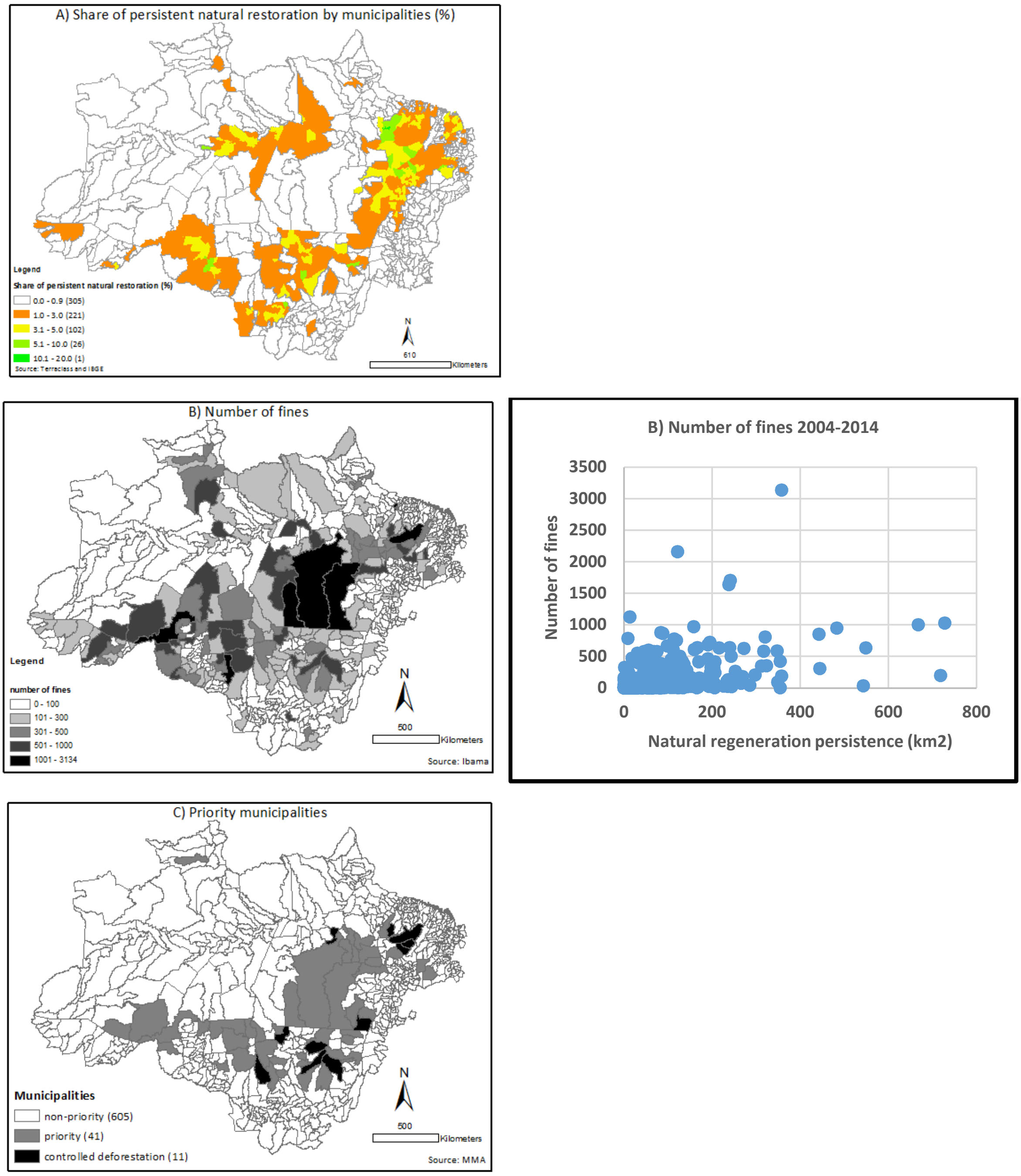

Figure S 6.1 – Distribution by the 657 municipalities of the selected variables/covariates (spatial and scatterplot) for the spatial cross-section analysis: A) natural restoration persistence; B) number of fines; C) priority municipalities; D) agriculture persistence; E) clean pasture persistence; F) non-forest share ; G) CAR share; H) population density; I) in-migrants population; J) roads/highways; K) annual rainfall; and L) annual average temperature.

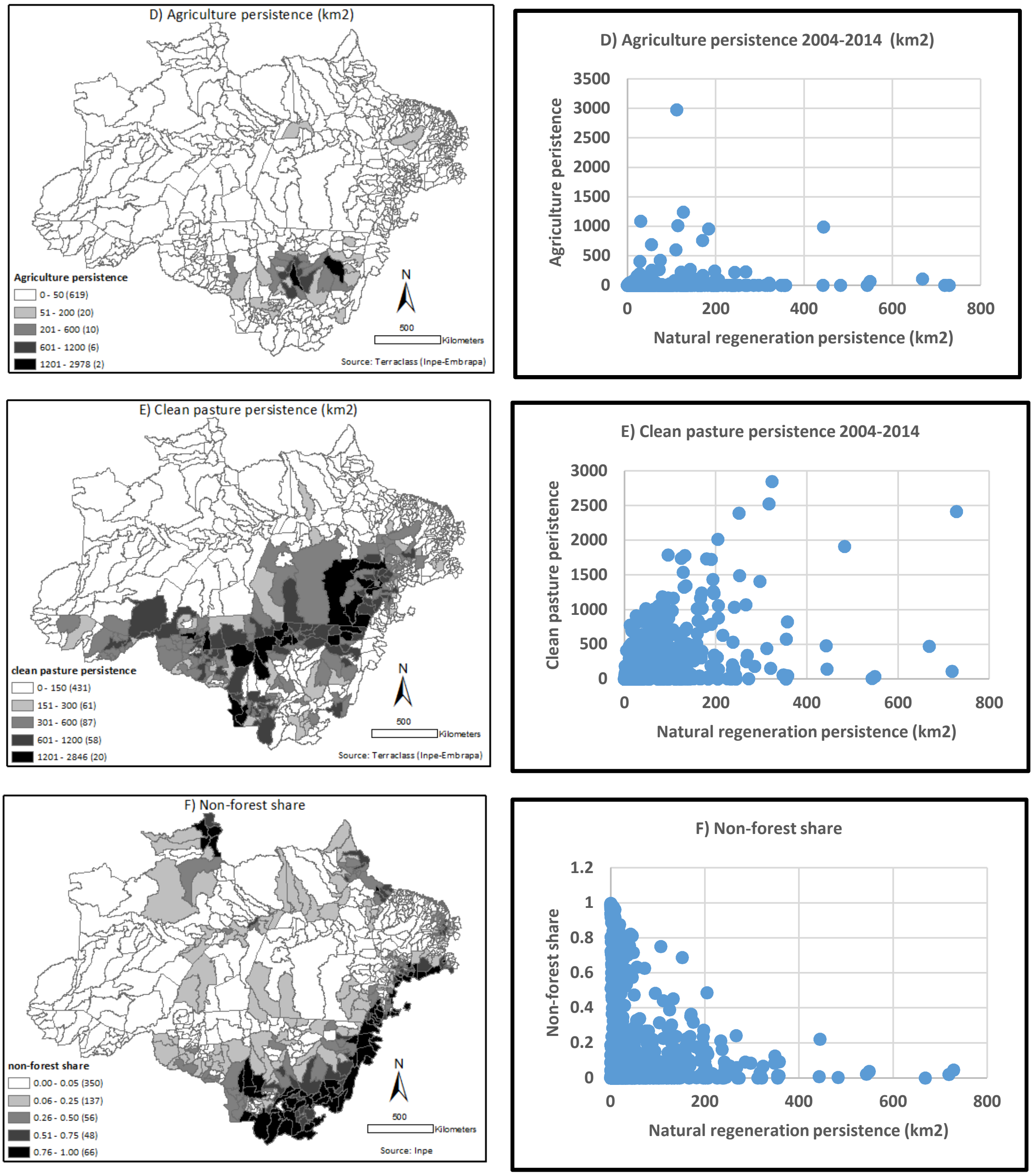

Figure S 6.1 (cont.)– Distribution by the 657 municipalities of the selected variables/covariates (spatial and scatterplot) for the spatial cross-section analysis: A) natural restoration persistence; B) number of fines; C) priority municipalities; D) agriculture persistence; E) clean pasture persistence; F) non-forest share ; G) CAR share; H) population density; I) in-migrants population; J) roads/highways; K) annual rainfall; and L) annual average temperature.

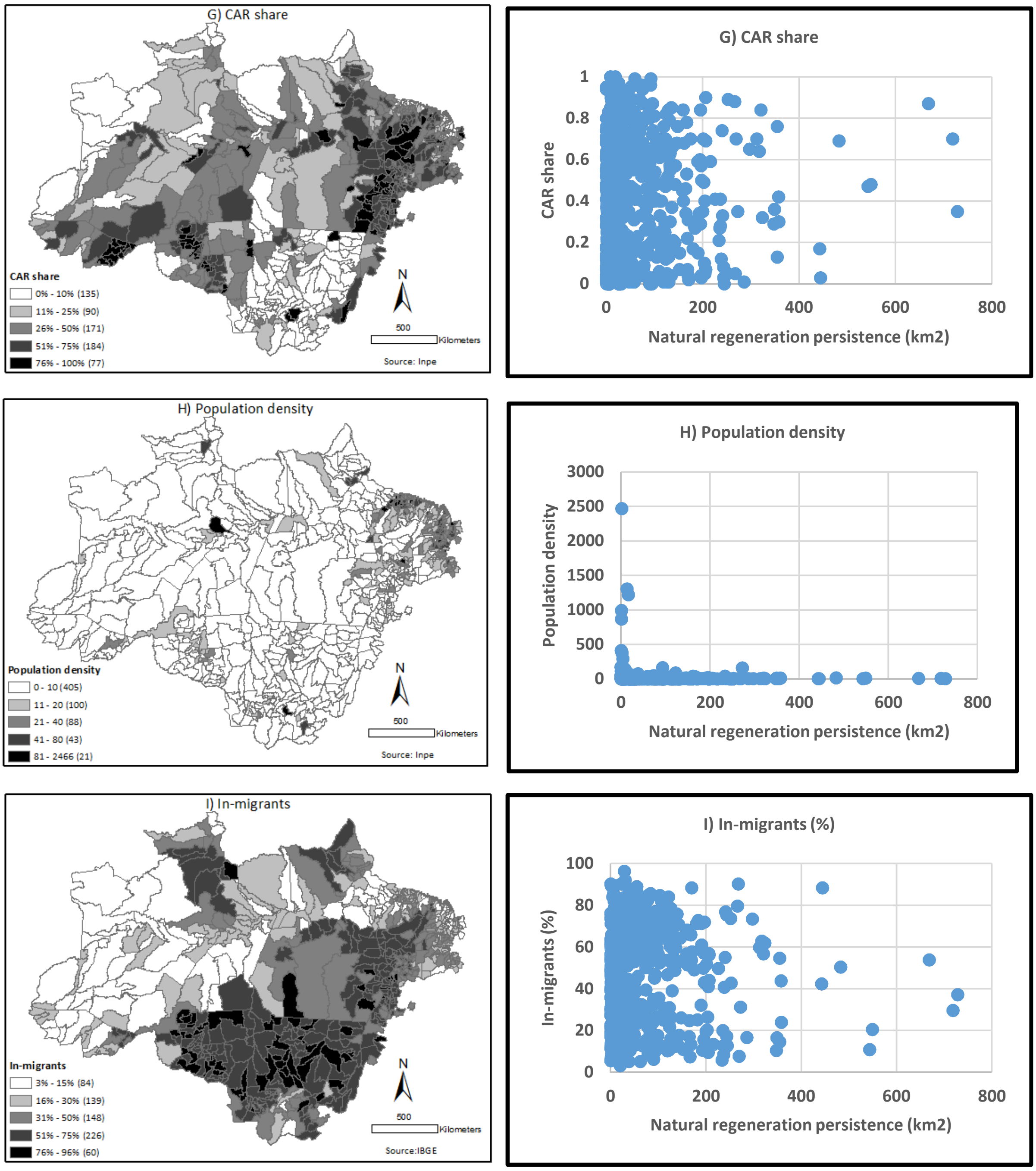

Figure S 6.1 (cont.) – Distribution by the 657 municipalities of the selected variables/covariates ((spatial and scatterplot) for the spatial cross-section analysis: A) natural restoration persistence; B) number of fines; C) priority municipalities; D) agriculture persistence; E) clean pasture persistence; F) non-forest share ; G) CAR share; H) population density; I) in-migrants population; J) roads/highways; K) annual rainfall; and L) annual average temperature.

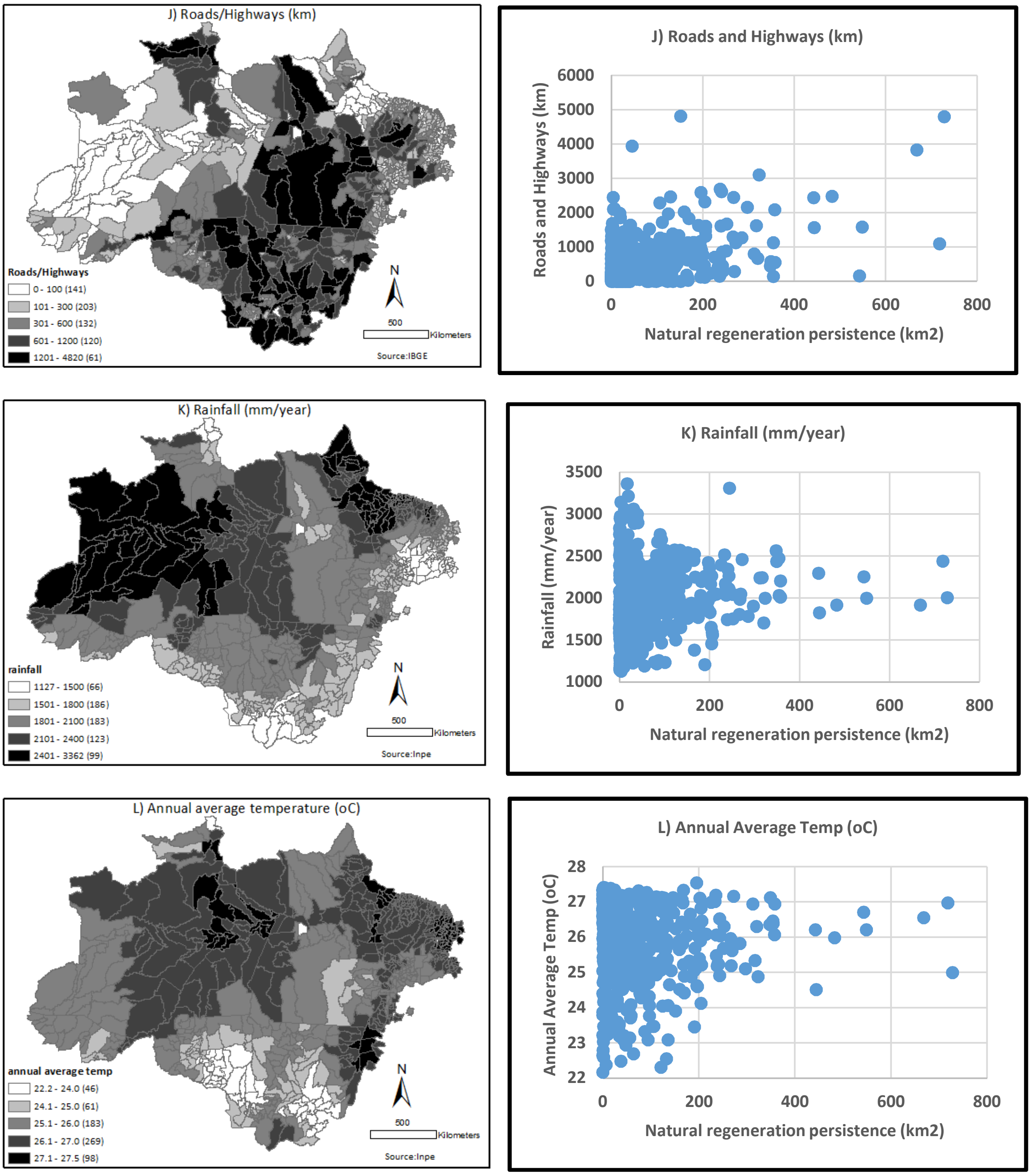

Figure S 6.1 (cont.) – Distribution by the 657 municipalities of the selected variables/covariates ((spatial and scatterplot) for the spatial cross-section analysis: A) natural restoration persistence; B) number of fines; C) priority municipalities; D) agriculture persistence; E) clean pasture persistence; F) non-forest share ; G) CAR share; H) population density; I) in-migrants population; J) roads/highways; K) annual rainfall; and L) annual average temperature.