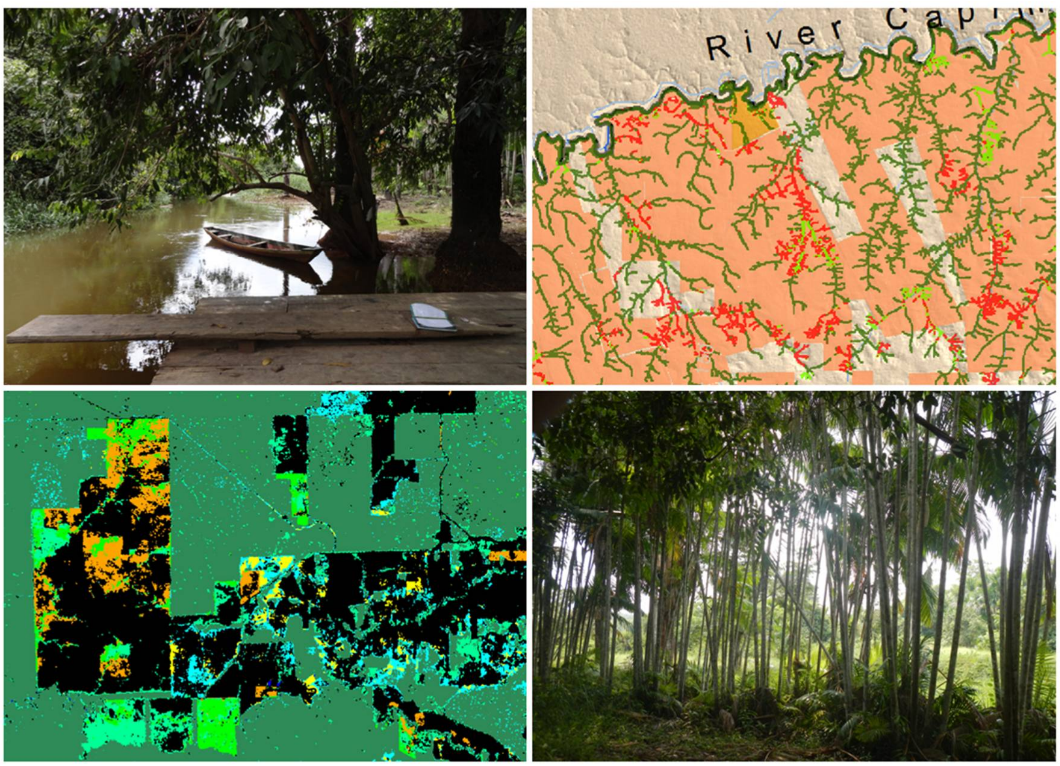
Beyond protected areas: Assessing the role of Legal Reserves and Permanent Preservation Areas for conserving tropical forests in private properties in the eastern Brazilian Amazon



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April 2016

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Beyond protected areas: Assessing the role of Legal Reserves and Permanent Preservation Areas for conserving tropical forests in private properties in the eastern Brazilian Amazon

Thesis submitted for the degree of Doctor of Philosophy as a Full Time PhD with

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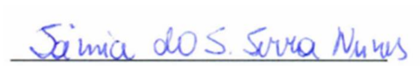
DECLARATION

I hereby declare that this work has been originally produced by myself for this thesis and it has not been submitted for the award of a higher degree to any other institution. Inputs from co-authors are acknowledged throughout.



Sâmia Nunes, Lancaster, April 2016.

“The decisions of our past are the architects of our present”

- Dan Brown, Inferno

I dedicate this thesis to my parents, Jananci and Lúcia, for their unconditional love and support to my studies since ever.

Dedico esta tese a meus pais, Jananci e Lúcia, pelo seu amor incondicional e pelo apoio a meus estudos desde sempre.

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ABSTRACT

Native vegetation covers about 60% of the national territory of Brazil, with 40% under some form of public protected area (conservation units and indigenous lands) and the remaining 60% located in private areas or public lands with no clear designation. The protection of forests on private land is therefore a vital part of any overall conservation strategy. In Brazil, the conservation of forest on private lands is regulated by the Brazilian Environmental Law (Law N° 12.651, 25 March 2012), commonly known as the Forest Code, and focus on two main mechanisms: Legal Reserves (LR) and Permanent Preservation Areas (APP in Portuguese). The aim of this thesis is to advance our understanding of some of the key challenges and opportunities facing forest conservation and restoration in the Brazilian Amazon by assessing the LR and APPs on private lands. Focused on Pará, the thesis provides the first assessment of the total LR deficit (LR that have been illegally deforested in the past) for any of Brazil´s Amazonian states as well as a uniquely comprehensive assessment of legal compliance with the protection and restoration of APPs, and critically examines implications for different actors and public policy. In Chapter 2 we found no evidence that riparian forests had been more effectively protected than non-riparian forests in the flagship municipality of Paragominas. Instead, deforestation was found to be comparatively higher inside riparian permanent preservation areas as recently as 2010, indicating widespread failure of private property owners to comply with environmental legislation. Moreover there was no evidence for higher levels of regeneration in deforested riparian zones than non-riparian zones, although property owners are obliged by law to restore such areas. A number of challenges limit efforts to improve the protection and restoration of riparian forests. These include limited awareness of environmental compliance requirements, better cartographic products and limitations in the technical capacity of the state and municipality governments. Considering the whole state of Pará, Chapter 3 shows that the total LR surplus (12.6 Mha) – based on the revised Forest Code – is more than five times the total area of deficit (2.3 Mha). Yet, of this total surplus, only 11% can be legally deforested (is in properties with >80% forest cover) and the remaining 89% is already protected by law but can be used (sold or rented) to compensate for areas that are under deficit. This analysis identifies that the majority of municipalities (111 out of 144) in the state could compensate their total LR deficit with surplus areas of LR within the same municipality, indicating compensation can always take place close to the source of the deficit. Maximizing the environmental benefits of achieving Forest Code compliance requires measures that go beyond the existing legal framework, including interventions to avoid further deforestation in places where it is still legal, compensate in close proximity to areas with legal reserve deficit and promote local restoration on degraded lands. Finally, Chapter 4 finds that, despite riparian APPs being mostly covered by forest in the state of Pará (63%), the area required to be restored by law (1 Mha) accounts for only about one-third of the deforested area that does not need to be restored following the 2012 revision of the Forest Code. This suggests that some important catchments in Pará may not recover fully functioning hydrological and ecological services, as around 2.7 Mha of consolidated APP are likely to remain deforested. We also demonstrated how coarse-scale mapping data consistently underestimates the extent of different APP areas, and thus the scale of the challenge presented by the compliance requirements of the forest code. In improving our understanding of the requirements and potential for forest compensation and restoration, through the mechanisms of APP and LR, offers a key advance for achieving environmental compliance in Pará and elsewhere in the Brazilian Amazon and the wider tropics.

Keywords: Riparian forest, Legal Reserve, deficit compensation, forest restoration, Forest Code, Remote Sensing, rural properties, Amazon.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

1. GENERAL INTRODUCTION

1.1. Tropical forests

Forests are critical to the provision of many ecosystem services, including the protection of hydrological flows and maintenance of water quality, protection of soil, climate regulation through carbon sequestration and storage, and the conservation of biodiversity (Daily *et al.*, 1997; Nasi *et al.*, 2002). Yet, in recent decades vast areas of forest have been converted for cattle ranching and agriculture: ~13 million ha of the world's forest were lost each year over the last decade and 16 million ha per year in the 1990s.

The world's total forest area is ~4 billion ha, or 31% of total land area, of which more than half is concentrated in only five countries: Russian Federation, Brazil, Canada, USA and China (FAO - Food and Agriculture Organization, 2010). The largest rain forest biome, the Amazon, is located in South America. The country contains the largest portion of remaining rain forest and the largest freshwater reservoir in the world (Margulis, 2003), holding c. 1.8 million species (Lewinsohn and Prado, 2005).

Humid tropical forests cover an area of 11 million km^2 and are distributed across Southeast Asia, Africa and South America (Pan *et al.*, 2011). These forests provide not only ecosystem services, but also economic goods. For example, they are extremely diverse, housing two-thirds of the world's terrestrial biodiversity (Pimm and Raven, 2000); play a critical role in sequestering carbon, storing up to 208 Pg of C (Saatchi *et al.*, 2011); help control diseases (e.g. biodiversity in forests can help to reduce local malaria transmission) (Hahn *et al.*, 2014); provide timber and non-timber products to millions of people (Pereira *et al.*, 2010); help reduce soil erosion, facilitating sediment deposition and organic matter accumulation (Paula *et al.*, 2012) and maintain hydrological cycles, temperature and precipitation (Lawrence and Vandecar, 2015).

In the last two decades, 50% of the original tropical forest extent has been lost as a result of agriculture and cattle ranching expansion (Skole and Tucker, 1993). The clearance and burning of carbon stored in wood releases greenhouse gases to the atmosphere that amount to ~12-20% of annual global carbon emissions (van der Werf *et al.*, 2009). Although the direct impacts of degradation are less severe than clear cutting, tropical forests are logged at about 20 times the rate at which they are deforested (Asner *et al.*, 2009) and 403 million ha of tropical forests are officially designated for timber production (Blaser *et al.*, 2011). Deforestation affects biological diversity in three different ways: loss of habitat, fragmentation and edge effects (Skole and Tucker, 1993). One of the most important impacts of fragmentation is on carbon storage, due to the damage on biomass, which can be lost in two different ways: (i) by fire with increased flammability and (ii) tree mortality near forest edges (Numata *et al.*, 2011). The portion of the remaining forest is more sensitive to edge effects such as wind disturbances and microclimate changes, promoting lianas proliferation and eases the access for hunters and non-forest animals and resulting in a net loss of biodiversity near edges (Skole and Tucker, 1993; Numata *et al.*, 2011).

Many conservation strategies have been implemented in order to reduce the human impact on tropical forests, including the creation of public protected areas, command and control regulations, incentive schemes and monitoring systems based on satellite imagery (Gardner *et al.*, 2009; Barreto and Araújo, 2012). However, despite efforts to conserve forests through protected areas, only 19% of total forest cover is under some form of protection (Heino *et al.*, 2015). Thus, conservation on private lands is also essential in order to safeguard biodiversity in the long-term (Soares-Filho *et al.*, 2006). For example, more than half of Brazilian native forests are located in private lands (Ferreira *et al.*, 2012).

1.2. Tropical Forests in the Amazon

Covering 6.5 million km^2, the Amazon forest is the largest remaining of tropical forest in the world. Brazil holds the largest part of this region: an area of 4.1 km^2 (Margulis, 2003) (Fig. 1.3). Amazonian forests play an important role in the scenario of global warming and provision of ecosystem services (Carvalho *et al.*, 2004; Leadley *et al.*, 2014), containing 60-80 billion tons of C, around 350 tons of biomass per hectare (Houghton *et al.*, 2001; Carvalho *et al.*, 2004), and approximately 25% of terrestrial species (Dirzo and Raven, 2003) and one-fifth of the world's freshwater (Margulis, 2003).

Furthermore, the Amazon is not only a homogeneous green carpet crossed by rivers. The Amazon basin encompasses a mosaic of ecoregion types, including *terra firma* rainforest, flooded riparian forest, seasonal forest, and even savannah. The interior landscape is dominated by moist forest, but riparian areas contain várzeas or flooded forest habitat. The southeast border is specially comprised of seasonal forest, while further south and east lies the Cerrado savannah ecoregion (Olson et al., 2001; Yale School of Forestry & Environmental Studies, 2016). Some regions in the Amazon, such as Guyana Shield in northeast and the lowlands of western Amazon are known as 'major wilderness areas', with concentrations of endemic species, retaining > 75% of their native vegetation and very low population densities (<five people per square kilometer) (Myers et al., 2000).

Yet the Amazon forest is also threatened by land-use change. According to the Brazilian government forest monitoring program PRODES, 20% of the forest of Brazilian Amazon has been converted to pasture and agriculture, mostly in the past 40 years. Deforestation is the major driver of biomass loss and atmospheric carbon emissions from land use: in 2012 Brazil was classified as the world's 7th largest emitter, responsible for 2.34% of the world's greenhouse emissions, or ~1.8 $GtCO_2e$. The deforestation in the Amazon is the main cause of this high ranking for Brazil (Aguiar *et al.*, 2012; WRI, 2012).

Another important source of change in the Amazon is the forest degradation through selective logging, forest fires and edge effects related to fragmentation (Numata *et al.*, 2011; Achard and Hansen, 2012). For example, in 2009, 14.1 million m^3 of round wood were extracted from the Brazilian Amazon, and at least 36% of this figure was illegal (Pereira *et al.*, 2010). Although less severe in terms of the intensity of damage, degradation can affect an area larger than the area deforested (INPE, 2013; Morton *et al.*, 2013), and rates can increase even when deforestation is declining (Aragão and Shimabukuro, 2010; Souza Jr. *et al.*, 2013b). Forest disturbance dramatically reduces carbon storage in Amazonian forests (Berenguer *et al.*, 2014) and could release ~0.1 billion metric tons of carbon to the atmosphere annually (Asner *et al.*, 2005).

In response to widespread concerns over deforestation, from 1995 the government started creating policies to stop the deforestation, e.g. rules for agriculture and cattle ranching licensing, penalties and monitoring by satellite imagery. However, such policies were ineffective and the market was the major ruler of the deforestation rates (Barreto and Araújo, 2012). More recently, from 2004, a set of public policies combined to civil society actions helped to reduce the deforestation in the Amazon in 79% between 2005 and 2013 (Fig. 1.1). These actions included command and control actions, creation of protected areas, commercial and financial embargoes, independent monitoring of deforestation and degradation and campaigns to avoid purchasing products from areas deforested illegally. For example, the government launched in 2004 the Action Plan for Prevention and Control of the Legal Amazon Deforestation (PPCDAm in Portuguese), which encompassed land tenure regularization, large-scale reserve expansion, monitoring and incentives to sustainable agricultural production systems (Barreto and Silva, 2010; Soares-Filho *et al.*, 2010; Barreto and Araújo, 2012; MMA - Brazilian Ministry of the Environment, 2004b).

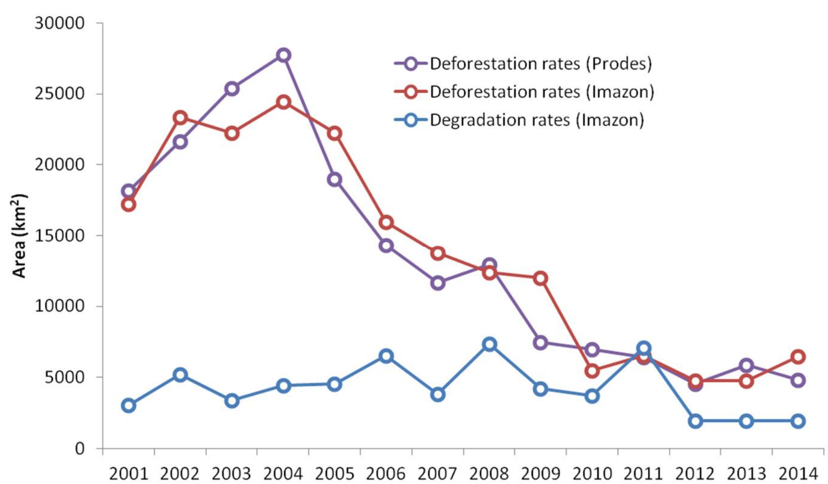

Figure 1.1. Annual deforestation and degradation rates in the Brazilian Amazon. Data from Imazon (Souza Jr. et al., 2013) and Inpe (National Institute for Space Research, 2014).

1.3. Conservation of forest on private lands in Brazil

About 60% of the national territory of Brazil is covered by native vegetation, with 40% under some form of public protected area (conservation areas in the public domain and indigenous lands) and the remaining 60% located in private areas (e.g. Legal Reserves and riparian forests) or public lands with no clear designation (Ferreira *et al.*, 2012; Soares-Filho, 2013). Public protected areas alone cannot ensure either the protection of biodiversity or the maintenance of critical ecosystem services across entire landscapes (Silva Dias *et al.*, 2002), including the effective conservation of hydrological catchments, with many headwaters located outside public protected area boundaries (Soares-Filho *et al.*, 2006). Thus, the protection of forests on private land is a vital part of any overall conservation strategy, helping sustain the delivery of critical ecosystem services, including maintenance of hydrological cycles, water quality, climate regulation through carbon sequestration and storage and the conservation of biodiversity (Daily *et al.*, 1997; Grimaldi *et al.*, 2014).

In Brazil, the conservation of forests on private lands is primarily regulated by the Brazilian Environmental Law (Law N° 12.651, 25 March 2012) (Brazilian Federal Government, 2012b), commonly known as the Forest Code. The goal of this law is to ensure that Brazilian society benefits from the goods and services provided by forests, through the conservation of native vegetation. It defines rules for the protection of Permanent Preservation Areas (APP, in Portuguese) and Legal Reserves (LR), selective logging, control and prevention of forest fires together with the economic and financial instruments necessary to achieve these objectives. The Forest Code essentially divides rural properties into two types of area: land for production and land dedicated to conservation and the sustainable management of natural resources. The latter is divided into the APP and LR, which are the focus of this thesis.

The APPs were created to protect particularly sensitive areas such as riparian vegetation, springs, steep slopes (>45°), hilltops and mangroves and are not limited to private property boundaries. This thesis focuses on riparian APPs, which are of particular importance in the context of private lands as they help maintain the provision of key ecosystem services, such as the prevention of soil erosion in agricultural systems, the maintenance of water flows and water quality, and the conservation of biodiversity and ecological connectivity (Rodrigues and Gandolfi, 2000; Lees and Peres, 2008). The management activities permitted in APPs is strictly limited: only low impact activities, e.g. ecotourism, are allowed in a specific portion, as well as the maintenance of agrosilvopastoral systems in areas deforested up to 22nd July 2008. Thereafter, deforestation is considered illegal and forests must be restored following any of the restoration options required by law, such as direct planting and assisted natural regeneration (Brazilian Federal Government, 2012b).

The Legal Reserve is the part of a private property that aims to promote the sustainable use of natural resources and the conservation of biodiversity. Economic activities, such as forest management for selective logging or harvesting of non-timber products, are permitted in LRs, following rules governing sustainable management and subject to authorization by the state environmental agencies. Deforestation is not allowed within the LR. According to the new Forest Code, the delimitation of the LR area in a rural property is based on the region where the property is located. In the Legal Amazon, the LR varies from 20 to 35 and 80% depending on the phyto-physiognomy (grasslands, *cerrado* and forest, respectively). In the other regions the LR is 20% of the property. Nevertheless, this definition can be more complex. For example, LR reductions (e.g. beneath 80% in the case of the Amazon) are allowed depending on the size of the property, region-specific regulations (e.g. areas that are zoned for agricultural development under state zoning plans) and timing of deforestation (Brazilian Federal Government, 2012b).

Any shortfall of forest cover that is required to comply with the Forest Code is commonly termed the LR and APP deficits. The forest cover additional to that required by law is termed the LR surplus, and there is no surplus for APPs. LR surplus can be disaggregated further into two categories: (i) surplus that is in excess of the minimum LR legal requirement which cannot be deforested but can be used to compensate properties that are in deficit (hereafter termed compensation-only surplus); and (ii) surplus that which is in excess of the minimum LR requirement and which can legally be deforested (i.e. for the Amazon biome areas of forest that are in excess of 80% of the property area - termed here deforestable surplus).

In order to offset a LR deficit on a particular private property, the new Forest Code provides two possibilities: forest restoration within the same farm that has the deficit or compensation of LR deficit by acquiring, either through renting or purchasing, forest surplus forest in another property. With the exception of APP area, where any past deforestation must be restored, the option for compensation means that landowners in deficit due to past deforestation can maintain their LR entirely outside the boundaries of the farm and do not need to retire land from production for restoration purposes. Trading amongst private properties for LR compensation can occur through mechanisms such as Environmental Reserve Quotas (CRA) and conservation easements (Brazilian Federal Government, 2012b; Zakia and Pinto, 2013), with an increasing number of initiatives seeking to facilitate such exchanges (such as the online legal reserve market place offered by *Bolsa Verde Rio*: www.bvrio.org).

Despite the comprehensive revision of the Forest Code in 2012 ongoing uncertainties over land tenure, e.g. land ownership rights and location of properties, make it very difficult to conduct an accurate assessment of land cover in rural properties or implement environmental legislation effectively (Barreto *et al.*, 2008; Brito and Barreto, 2011). To address this, the Brazilian government created the Environmental Rural Property Register (CAR, in Portuguese, first introduced in the state of Pará in 2006), as a georeferenced register of private properties, that has been instrumental in helping to both assess and promote compliance with environmental regulations, curb deforestation and foster more effective economic and environmental planning.

The Brazilian environmental law states that by December 2017 all rural properties in the country must be registered in CAR (Brazilian Federal Government, 2012a, 2012b). Up to now, 66% of the country is registered in CAR (from the area suitable for registry, that is, the area where CAR is allowed), distributed as it follows: 82.7% of North region is registered in Car; 65.2% for Southeast; 64.1% for Central-West; 37.3% for Northeast and 33.1% for South region (Fig. 1.2).

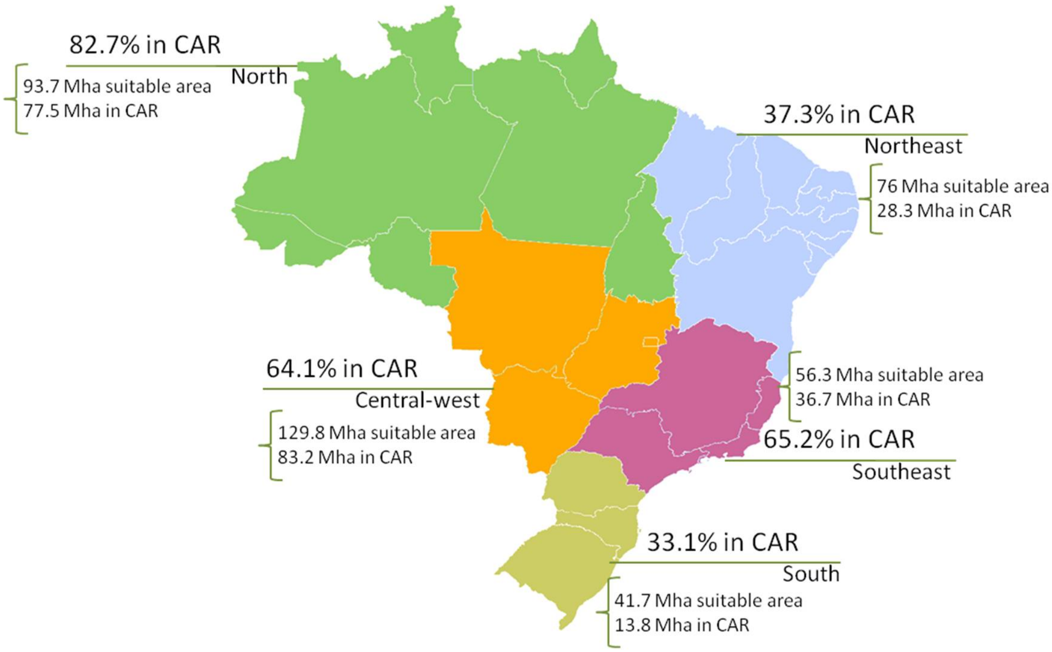

Figure 1.2. CAR coverage in Brazil related to the area suitable for registry by region. Data from (MMA, 2016).

Most of the Amazon region is concentrated in the North region that holds the largest percentage of areas registered in CAR system in Brazil. This is especially due to the government policies to stop deforestation, such as PPCDAm and the creation of the MMA's Red List (list of the most deforesting municipalities in the Amazon). MMA set two main criteria for municipalities to be removed from the list: reducing deforestation to less than 40 km^2 a year and implementing CAR in at least 80% of the municipality. The penalties for the municipalities to be included in the MMA's Red List are commercial and financial embargoes and campaigns to avoid purchasing products from areas deforested illegally, among others (MMA - Brazilian Ministry of the Environment, 2004b; Neves *et al.*, 2015).

1.4. Key knowledge gaps and thesis objectives

This thesis focuses on advancing our understanding of some of the key challenges and opportunities facing forest conservation and restoration in the Brazilian Amazon, including the assessment of LR and APP areas that have been illegally deforested in the past, as well as patterns of LR surplus and deficit. The thesis is motivated by recognition of the opportunities to improve science-based decision making for land management across the humid tropics. The thesis makes novel contributions by combining inputs from ecology, geoprocessing and remote sensing to address some of the major knowledge gaps facing the implementation of Brazil´s flagship environmental legislation, the Forest Code, while also helping to raise awareness among stakeholders and decision makers involved in this vital work at local, regional and national levels. Whilst the questions posed by this thesis are focused on the Brazilian context they are globally relevant, particularly in light of the strong interest in replicating Brazil´s approaches to curbing deforestation elsewhere.

The thesis is structured around three chapters that address key knowledge gaps facing efforts to improved compliance with Brazilian environmental law. Major knowledge gaps include: (i) the lack of an accurate and representative georeferenced register of private properties for any Brazilian state, (ii) a lack of detailed and reliable Geographic Information Systems (GIS) and remote sensing products at large scales (e.g. land cover and water course maps), and (iii) the complexity of Brazilian environmental laws that have led to widespread uncertainty, misunderstandings and controversies among different sectors and actors. The thesis is structured as follows:

- ***Chapter 2*:** A 22 year assessment of deforestation and restoration in riparian forests in the eastern Brazilian Amazon.

Knowledge gap: Brazilian environmental law imposes more restrictions on private landowners preventing land-use change in riparian forests than in non-riparian forest areas, reflecting recognition of their importance for the conservation of biodiversity and key ecosystem services. However, the effectiveness of the legal protection afforded to riparian vegetation in the Brazilian Amazon has been poorly assessed, because: (i) more accurate cartographic products are required to determine the extent of riparian APPs, (ii) a pervasive lack of clarity about what is legally considered to be a riparian APP under Brazilian law and (iii) reliable information on property boundaries and registration in the CAR system, which is required to estimate APP deficit. In this Chapter we evaluated deforestation and regeneration of riparian forests over the past two decades in order to better understand the pattern of forest loss and recovery through time in riparian APPs.

Research questions: (i) does the temporal pattern of deforestation within RAPPs (riparian permanent preservation areas) follow the same pattern of forest loss observed in areas outside RAPPs? In other words, do RAPPs offer any additional protection to riparian forest? (ii) In areas that have already been cleared, is the level of forest regeneration inside RAPPs similar to that observed outside RAPPs? And (iii) do environmental liabilities differ between specific types of land tenure, including private properties, agrarian reform settlements, indigenous land or untitled (unregistered) private lands?

- ***Chapter 3***: Compensating for past deforestation: assessing the legal forest surplus and deficit of the state of Pará, eastern Amazonia.

Knowledge gap: Up to 80% of each private rural properties in the Brazilian Amazon is protected by law through the Legal Reserve (LR) mechanism of the Federal Forest Code. However, our understanding of the discrepancies in level of forest protection on private lands as obligated by the law versus what occurs in practice remains very poor. There are three mains reasons for this: (i) the historic lack of a minimally accurate and representative georeferenced register of private properties for any Brazilian state, due to the insufficient technical expertise within state governments, (ii) a lack of detailed and reliable GIS and remote sensing products with a resolution consistent with the scale of individual properties and (iii) the complexity of Brazilian environmental laws that have led to uncertainties on how to apply regulations and estimate legal liabilities. Here we assessed the total LR deficit and surplus for the state of Pará and compare levels among different sized properties and across 144 municipalities.

Research questions: (i) What is the LR deficit and surplus for the entire state of Pará?; (ii) What proportion of the total surplus can be considered deforestable versus compensation-only surplus? (iii) How is the total deficit and surplus for the state distributed across properties of different sizes?; and (iv) What is the capacity of each municipality to compensate its LR deficit within the same or adjacent municipalities?

- ***Chapter 4***: Assessing the conservation status of riparian forests in the eastern Brazilian Amazon

Knowledge gap: The protection of riparian forests is of particular conservation importance as they help maintain the provision of key ecosystem services, such as the prevention of soil erosion in agricultural systems, the maintenance of water flows and water quality, and the conservation of biodiversity and ecological connectivity. However, despite the significance of the Forest Code as the basis of environmental protection on private properties in Brazil, the effectiveness of the legal protection afforded to riparian vegetation in APPs has been very poorly assessed at large spatial scales, particularly in the Brazilian Amazon. There are at least two main reasons for this: (i) the accuracy of maps of riparian forests and APPs more generally in the Amazon region is limited by lack of sufficiently fine-scale land cover and hydrography maps to estimate drainage networks and the width of water courses (1:50.000 at least); and (ii) the extent of legal liabilities (such as the deficit of riparian APP in a given private property compared to what is required by law) depends critically upon access to an accurate georeferenced register of private properties.

Research questions: (i) What is the current status of riparian APPs across the state, including their total extent, forested extent and total area that is required to be restored by law? (ii) What uncertainty and potential bias is introduced into assessments of riparian forest when using coarse or fine-resolution land-cover and hydrological data?

1.5. Study regions

The focus of this thesis is the 1.25 million km^2 state of Pará, which is the second largest state in Brazil and is larger than countries such as South Africa and Colombia. Pará is located in the eastern Brazilian Amazon (Fig. 1.3). Its economy is mostly made up by extractive industry (e.g. iron, bauxite, wood, charcoal), agriculture (e.g. palm oil and cassava) and cattle ranching (Pará has the fifth largest cattle herd in Brazil – with 17 million heads in the 2013 census) (IBGE - Brazilian Institute of Geography and Statistics, 2013). Despite the state of Pará having about 55% its territory, or 685,575 km^2, in some form of public protected area or indigenous reserve (Brazilian Ministry of the Environment and National Indian Foundation, 2013), 21% of the state was deforested by 2014 (INPE -National Institute for Space Research, 2014), and it continues to have one of the highest rates of deforestation in the Amazon.

In order to reduce deforestation rates and increase the property area registered under the CAR system, the government launched programs such as the Green Municipalities Program in partnership with municipalities, civil society, private initiatives and the Public Prosecution Service (Whately and Campanili, 2013). Despite considerable success in reducing deforestation, many challenges remain to reduce the c. 5-6000km^2 that are still cleared every year and to achieve compliance with the revised Forest Code. A major barrier is land tenure with the tenure situation of private land across Pará remaining in a very confused state, with 39% of the territory - mainly the eastern portion - presenting tenure irregularities. The remaining 61% that has defined tenure includes protected areas, agrarian reform settlements and registered properties. Increasing the area registered in CAR would improve greatly the process of tenure regularization in Pará, even if it does not constitute a formal registry of legal tenure (Brito *et al.*, 2013).

Figure 1. 3. Map of study area. (a) State of Pará and (b) Paragominas municipality.

Within the state of Pará this thesis includes a case study of the municipality of Paragominas (Fig. 1.2), because: (1) it experienced high levels of deforestation during the period of analysis; (2) it is widely recognized as exemplifying recent efforts by state and municipal government, as well as civil society, to reduce deforestation; and (3) it has a nearly complete and accurate registry of land titles compared to the other Amazonian municipalities (Guimarães *et al.*, 2011; Viana *et al.*, 2012).

1.6. Thesis structure

The data chapters in this thesis have all been written for publication: Chapter 2 was published in *Environmental Conservation Journal*; Chapter 3 was published in *Land Use Policy Journal* and Chapter 4 will be submitted for review to Forest Ecology and Management. The structure of this thesis is therefore made up of stand-alone chapters linked by the common theme of the challenges and barriers facing compliance of private properties with the Brazilian Environmental law regarding the protection of Legal Reserves (LR) and Permanent Preservation Areas (APP). Chapter 5 provides a summary of the findings related to each of the research aims, recommendations for conservation policies and main challenges and barriers for forest restoration and compensation of LR deficits, as well as highlighting future research needs.

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Chapter 2

2. A 22 year assessment of deforestation and restoration in riparian forests in the eastern Brazilian Amazon

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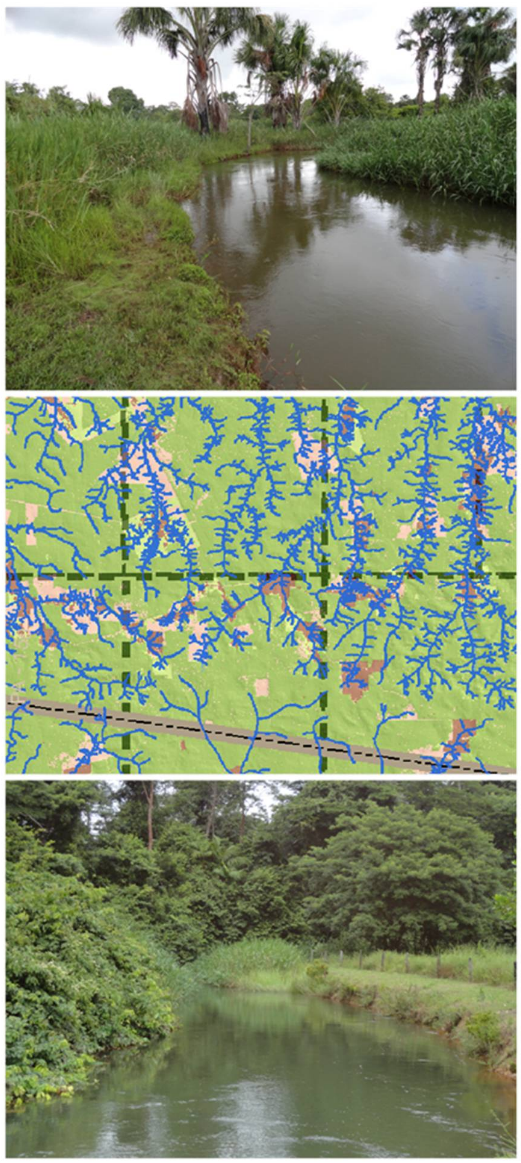

A 22 year assessment of deforestation and restoration in riparian forests in the eastern Brazilian Amazon

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2.1. Abstract

Brazilian environmental law imposes more restrictions on land-use change by private landowners in riparian forests than in non-riparian forest areas, reflecting recognition of their importance for the conservation of biodiversity and key ecosystem services. A 22-year time series of classified Landsat images was used to evaluate deforestation and forest regeneration in riparian permanent preservation areas over the past two decades, focusing on the municipality of Paragominas in the state of Pará in eastern Amazonia. There was no evidence that riparian forests had been more effectively protected than non-riparian forests. Instead, deforestation was found to be comparatively higher inside riparian permanent preservation areas as recently as 2010, indicating a widespread failure of private property owners to comply with environmental legislation. There was no evidence for higher levels of regeneration in riparian zones, although property owners are obliged by law to restore such areas. A number of factors limit improvements in the protection and restoration of riparian forests. These include limited awareness of environmental compliance requirements, the need for improved technical capacity in mapping the distribution and extent of riparian forests and the boundaries of private properties, and improved access to the financial resources and technical capacity needed to support restoration projects.

Keywords: Brazilian environmental law, forest restoration, Landsat classification, permanent preservation areas, riparian forest

2.2. Introduction

Forests support the provision of many ecosystem services, including the protection of hydrological flows and maintenance of water quality, protection of soil, climate regulation through carbon sequestration and storage, and the conservation of biodiversity (Daily *et al.,* 1997; Nasi *et al.,* 2002; Grimaldi *et al.,* 2014). Yet, c. 13 million hectares of the world's forests were lost each year over the last decade (FAO [Food and Agriculture Organization of the United Nations] 2010), mainly due to conversion for cattle ranching and agriculture (Margulis, 2003; FAO, 2010). Between 2000 and 2010, Brazil alone contributed to 44% of the global net loss of forest, most of which can be attributed to deforestation in the Amazon (FAO, 2010; Barreto and Araújo 2012). However, Brazil has also shown the largest decline in annual forest loss over the past decade, primarily owing to a marked drop in Amazonian deforestation since 2005 (Hansen *et al.,* 2013).

In attempting to protect forests from clearance and degradation, the Brazilian government has created forest protected areas on both public and private land (Chape *et al.,* 2005; Schmitt *et al.,* 2009; Veríssimo *et al.,* 2011). Approximately 46% of the Brazilian Amazon was under some form of public protection in 2012 (A. Rolla, Brazilian Socioenvironmental Institute/Instituto Socioambiental [ISA], personal communication 2012). However, public protected areas alone are likely to be inadequate in ensuring either the protection of biodiversity or the maintenance of critical ecosystem services, many of which depend upon the conservation of areas of forest across entire landscapes, and not on isolated protected areas (Silva Dias *et al.,* 2002; Soares-Filho *et al.,* 2006). For example, protected areas can be less effective at conserving hydrological catchments then preventing deforestation, as headwaters can be located outside protected area boundaries (Soares-Filho *et al.,* 2006). Instead, networks of public and private protected areas, supported by strategic ecological–economic zoning plans, are needed to ensure the maintenance of locally and regionally relevant ecosystem services, as well as maintain habitat connectivity, ensure population viability in more isolated forest remnants and facilitate species migrations (Peres *et al.,* 2010).

The conservation of forests in private lands is therefore a vital part of any overall conservation strategy for the Amazon (Soares-Filho *et al.,* 2006; Lees *and* Peres, 2008; Peres *et al.,* 2010; Ferreira *et al.,* 2012). Although uncertainties about land tenure (such as land ownership rights and location of properties) make it difficult to conduct a comprehensive assessment of land cover change on private lands (Barreto *et al.,* 2008; Brito and Barreto, 2011), current estimates suggest they hold c.60% of the remaining native vegetation in Brazil as a whole (Ferreira *et al.,* 2012; Soares-Filho, 2013).

The protection of riparian forests is of particular importance in private lands as they help maintain the provision of key ecosystem services, such as the prevention of soil erosion in agricultural systems, the maintenance of water flows and water quality, and the conservation of biodiversity and ecological connectivity (Rodrigues and Gandolfi, 2000; Lees and Peres, 2008; Castello *et al.,* 2013; Grimaldi *et al.,* 2014). Their importance is often recognized in environmental legislation, with more restrictions preventing land-use change in riparian forests than in non-riparian forest areas in private properties (as is the case in Brazil under the 2012 federal Forest Code Law No. 12.651, see URL http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12.651.htm) (Sparovek *et al.,* 2010), as well as in other countries (for example Belize, Costa Rica, the USA and Australia). In Brazil, only low impact activities (such as ecotourism) are allowed in riparian areas (alongside other particularly sensitive areas such as springs, steep slopes and hilltops, jointly termed permanent preservation areas, and abbreviated to APPs in Portuguese). Whilst deforestation within APPs is only permitted in exceptional circumstances (for example for public projects), depending on the region, between 20 and 80% of the area outside APPs can be deforested in a given private property.

Despite their importance, the effectiveness of the legal protection afforded to riparian vegetation in APPs (hereafter termed RAPPs) in the Brazilian Amazon has been poorly assessed. There are at least three main reasons for this. First, although geographic information systems (GIS) and remote sensing products are essential for effective law enforcement (Firestone and Souza, 2002), we are not aware of any studies that map water courses and examine land cover change in riparian and non-riparian vegetation over a decadal time-scale. Second, the difficulties of assessing the protection afforded by RAPPs have been exacerbated by a long period of regulatory confusion and uncertainty surrounding the definition of the Brazilian Forest Code, which lasted until the revised law came into force in October 2012 (Garcia, 2012). Third, assessing the extent of legal liabilities (such as deficit of RAPP in a given private property compared to what is required by law) depends upon access to an accurate georeferenced register of private properties. However, less than ten Brazilian states have initiated the registration of their private properties in the government database (the Environmental Rural Property Register, abbreviated to CAR in Portuguese), and, of these, the Amazonian states of Pará and Mato Grosso States are the most advanced. Nevertheless, only 16% of the 144 municipalities in Pará have more than 80% of their private land cover registered in the CAR system (SEMA/Imazon, 2016).

Here we examine patterns of deforestation and forest restoration inside and outside RAPPs during the most intense period of deforestation in the Amazon, which occurred between 1988 and 2010. We focus on the 1.9 million hectare municipality of Paragominas, located in the state of Pará, because: (1) it experienced high levels of deforestation during the period of analysis; (2) it is widely recognized as exemplifying recent efforts by state and municipal government, as well as civil society, to reduce deforestation; and (3) it has a nearly complete and accurate registry of land titles compared to the other Amazonian municipalities (Guimarães *et al.,* 2011; Viana *et al.,* 2012; Gardner *et al.,* 2013). We address three specific questions: (1) does the temporal pattern of deforestation within RAPPs follow the same pattern of forest loss observed in areas outside RAPPs? In other words, do RAPPs offer any additional protection to riparian forest? (2) In areas that have already been cleared, is the level of forest regeneration inside RAPPs similar to that observed outside RAPPs? And (3) do environmental liabilities differ between specific types of land tenure, including private properties, agrarian reform settlements, indigenous land or untitled (unregistered) private lands?

2.3. Materials and Methods

2.3.1. Study area

The focal municipality of Paragominas is situated at 3°00’00’’S and 47°21’30’’W, in the east of Pará State in the eastern Brazilian Amazon (Fig. 2.1a). In 2010 the municipality had a population of 98,000 people and a gross domestic product of R$ 1.2 billion, mostly from agriculture, industry and services (for example tourism, health care and entertainment) (IBGE [Brazilian Institute of Geography and Statistics] 2010).

Throughout the process of occupation, over the last 40 years Paragominas has experienced a number of economic cycles that have driven changes in land use. Recent occupation started in the 1960s, with the construction of the Belém-Brasília (BR-010) highway at a time when deforestation was encouraged by the Brazilian government as the main condition for establishing land ownership (Almeida, 1996). Between 1960 and 1970, the predominant land uses were slash-and-burn agriculture and cattle ranching (Uhl *et al.,* 1988). From the 1980s until the mid-1990s, logging became the main economic activity, with more than 300 sawmills being established in the municipality in less than two decades (1970–1987) (Uhl and Vieira, 1989; Veríssimo *et al.,* 2002; Brito *et al.,* 2010). More recently, the decline in wood availability and the increase in profitability of other land uses led to a period of economic diversification that included the expansion of mechanized agriculture, improvements in the productivity of cattle ranching, reduced impact selective logging, mining (principally for bauxite) and reforestation with both native and exotic species (Pinto *et al.,* 2009).

The occupation process led to the cumulative deforestation by 2010 of an area of 8600 km^2 in Paragominas, or c.44% of the total municipal area (INPE [Brazilian National Institute for Space Research] 2010). In 2008, Paragominas was included in the Ministry of the Environment Red List as one of the 36 most deforesting municipalities in the Amazon (MMA [Brazilian Ministry of the Environment] 2008). Since entering the list, Paragominas was targeted by federal government actions to control deforestation, including an intensified monitoring campaign by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and restrictions on credit and trading of agricultural commodities (Guimarães *et al.*, 2011; Viana *et al.*, 2012).

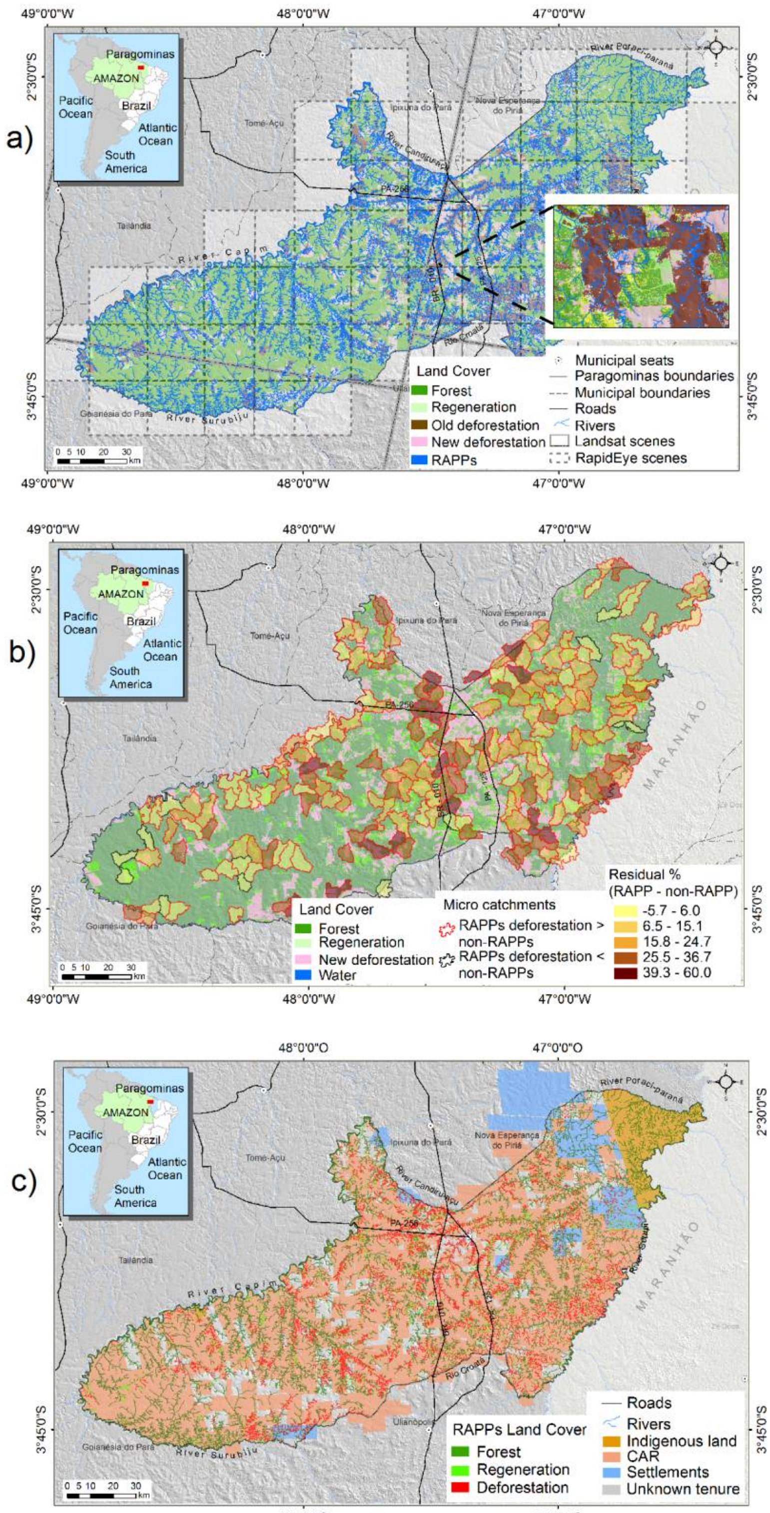

Figure 2.1. Maps of riparian permanent preservation areas (RAPP) analysis. (a) four Landsat scenes, land-cover classes and RAPPs in the municipality of Paragominas in Pará; (b) difference in relative

deforestation inside and outside RAPPs across 190 micro catchments in 2010; and (c) RAPPs detected in 2010 by land tenure (private properties registered in CAR, settlements, indigenous land and unregistered private lands).

The Brazilian Ministry of the Environment set two main criteria for municipalities to be removed from the Red List: reducing deforestation to less than 40 km^2 a year and implementing the environmental property register (CAR) in at least 80% of the municipality. To meet those requirements, the municipal government of Paragominas collaborated with the local farmers' union, and, in 2008, launched the *Paragominas Município Verde* (Paragominas Green Municipality) project, which focused on reducing illegal deforestation and supporting the registration of properties under CAR. This initiative had the cooperation of the state government and various non-governmental organizations (including the Amazon Institute of People and the Environment [Imazon] and The Nature Conservancy [TNC]). In March 2010, Paragominas became the first municipality in the Amazon to be removed from the Red List (Brito *et al.,* 2010; Guimarães *et al.,* 2011).

2.3.2. Image processing and mapping riparian areas of permanent preservation

We processed a 22-year time series (1988–2010) of Landsat images (see Supplementary information for image processing) in four main steps: pre-processing (georeferencing, haze correction and atmospheric correction), spectral mixture analysis, normalized difference fraction index (Souza Jr *et al.,* 2005) and a decision-tree land-cover classification (Souza and Siqueira, 2013; Souza Jr *et al.,* 2013b). In order to assess deforestation and regeneration inside and outside RAPPs during the last two decades, deforestation and regeneration maps were produced every two years from 1988 to 2010. In addition, we prepared a single map of RAPP extent (Brazilian Law N^{o}. 4.771, 15 September 1965), showing the location of RAPPs, based on Rapideye (2009/2010), Landsat (2010) and SRTM images (Souza Jr *et al.,* 2013a). We undertook an accuracy assessment of the 2010 Paragominas land cover in order to validate the Landsat classification, using RapidEye high-resolution images as a reference data (Powell *et al.,* 2004) (see Supplementary information, sections S2.9.6, S2.9.9).

Each deforestation map was combined with the RAPP map to assess forest loss per year within and outside riparian areas. Changes in forest cover prior to 2010 were assessed across the municipality as a whole, and also within 190 individual microcatchments (selected to be of approximately equal size, c. 5000 ha; see Supplementary information, section S2.9.5) to quantify geographical variability in deforestation patterns within the municipality. Linear regressions were used to compare RAPP and non-RAPP deforestation between years and catchments. We tested whether there was any difference between the regression line between RAPPs and non-RAPPs and the 1:1 line using an analysis of covariance.

To analyze forest regeneration, we assessed the age of all secondary forest areas mapped in 2010 (Supplementary information, section S2.9.5) based on the history of RAPP deforestation and regeneration throughout the 22-year study period. Regenerating forests younger than four years old were considered as deforestation in the analysis, as they cannot be distinguished from agricultural fallow areas (Roberts *et al.,* 2002).

Finally, the deforestation detected in 2010 was used to compare environmental liabilities (such as the proportion of deforested RAPPs that should be covered by vegetation; Brazilian Federal Law No. 12.651, 25 March 2012), between different types of land tenure (private properties, settlements, indigenous land and unregistered private lands) (see Supplementary information, section 2.9.8).

For the purposes of our study, all mapped streams and rivers were considered to be subject to enforcement as defined by Brazilian law. However, there remains considerable uncertainty as to what regulating authorities actually define as a RAPP in practice, particularly in areas where water flows may have been altered due to historical land-use change, and in areas where water flow may temporarily cease during particularly dry periods. This uncertainty could have a major bearing on any attempt to define what constitutes riparian vegetation, as small streams (1st and 2nd order) represent the majority (c.75%) of water courses mapped.

2.4. Results

2.4.1. Deforestation of RAPPs in Paragominas during last two decades

A total of 129,342 ha of Paragominas were defined as RAPP by our analysis, accounting for<7% of the municipality area. In 2010, 44% (56,369 ha) of this area was deforested (cumulative deforestation). When combining both currently deforested and regenerating areas, the total area of RAPP in the municipality that has been deforested at some time in the past rises to c. 49% (63,502 ha). Primary forest (undisturbed + degraded forests) accounts for 50.9% (65,839 ha) of the area. (Fig. 2.1a, Table 2.1). Between 1988 and 2010, Paragominas lost 25% of all its riparian forests, a decrease of 22,200 ha, from 88,000 to 65,800 ha.

In general, we found a very similar pattern of deforestation during 1990–2010 for both RAPPs and non-RAPPs in Paragominas, with a parallel increase in deforestation until 2004, followed by a subsequent decrease from 2004 to 2010 (Fig. 2.2). Comparing between different years of the study period, the proportion of deforestation in RAPPs (of total RAPP area) is very similar to the proportion of deforestation in non-RAPPs (R^2 = 0.87), the regression line indicating matching deforestation patterns (χ^2<0.01; $\rho \geq$ 0.99; df = 6; (Fig. 2.3a). By contrast, when comparing levels of deforestation inside and outside RAPPs across 190 micro catchments in 2010, there was also a strong positive relationship between deforestation inside and outside RAPPs (R^2 = 0.80), although deforestation was relatively greater inside RAPPs for that year (Fig. 2.3b; comparison between observed and 1:1 line: χ^2 = 8.69; ρ = 0.003; df=4).

In 2010, there was a high level of geographical variability in deforestation across the municipality for the 190 micro catchments (Fig. 2.1b). By plotting the difference in relative (standardized by forest area) deforestation for RAPP and nonRAPP forests for each catchment, we found that the most intensive clearance of RAPPs was concentrated in the central region of Paragominas, close to main highways. Catchments where overall deforestation was lower, the difference between deforestation inside and outside RAPPs was relatively small and generally located in the more remote areas, being concentrated in the north-east (which includes an indigenous protected area) and the south-west (which includes a large certified logging concession) (Fig. 2.1b).

Table 2.1. Land-cover classes of RAPPs. Area (ha) and proportion (%) of each land-cover class that makes up the total area of RAPPs in Paragominas, Pará, Brazil, up to 2010.

Classes	Area (ha)	Area (%)	Class description
Primary forest	65,839	50.9	Forest not deforested over time + degraded forest
Regeneration	7,133	5.5	Detected as regeneration in 1988
New deforestation	22,276	17.2	Deforestation since 1990 (increment)
Old deforestation	34,093	26.4	Non-forest areas + deforestation detected in 1988
Total	**129,342**	**100.0**	

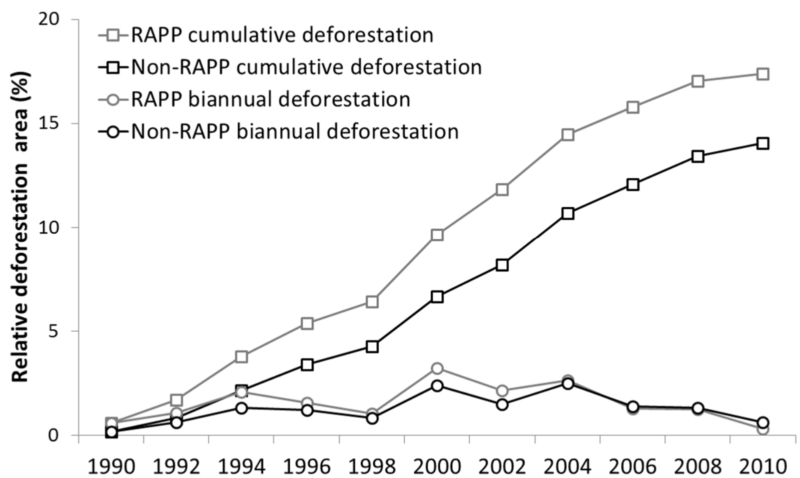

Figure 2.2. Relative biannual and cumulative deforestation in riparian permanent preservation areas (RAPPs) and non-RAPPs between 1990 and 2010 in Paragominas.

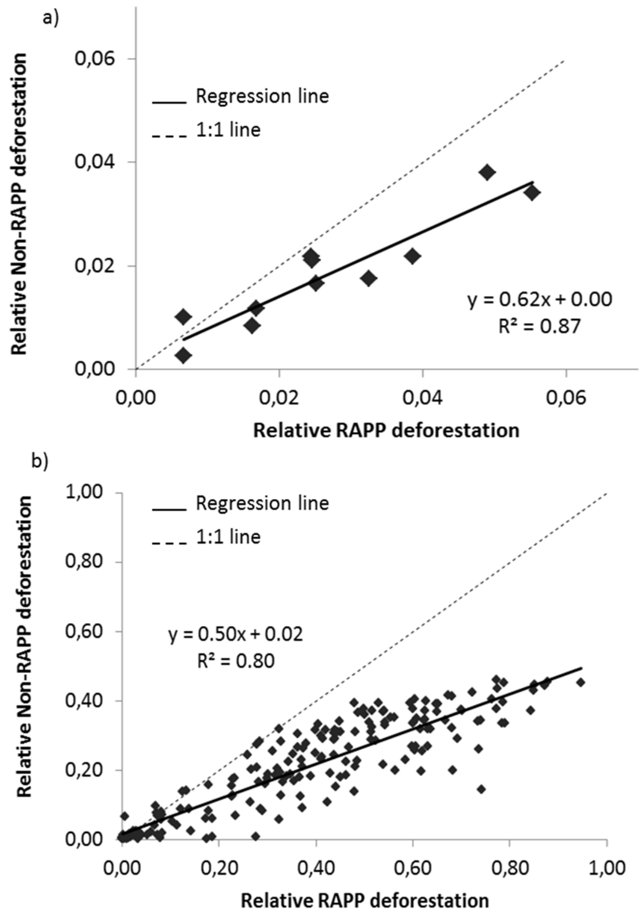

Figure 2.3. Relative deforestation in riparian permanent preservation areas (RAPPs) and non-RAPPs in Paragominas. (a) points in black represent years of analysis from 1990 to 2010 and (b) points in black represent the 190 micro catchments for 2010. Fitted line represents best fit from regression analysis. The 1:1 line represents the expected line if RAPPs and non-RAPPs were deforested at the same rate.

2.4.2. Regeneration of riparian forests

The relative area (%) of RAPPs and non-RAPPS that were occupied by regenerating forests in the time series was very similar (Fig. 2.4). Of the total RAPP that was mapped either as regeneration or deforestation in 2010 (63,680 ha), 28% (17,555 ha) was classified as deforestation every two years after 1988; 55% (34,925 ha) was classified as deforestation but under regeneration at some point between 1988 and 2010; and 17% (11,198 ha) was classified as regeneration in 2010 (Fig. 2.4a). Similar relative values were found outside RAPPs: 28% (204,346 ha) has been classified as deforestation every year since 1988, 56% (401,058 ha) as deforestation following prior regeneration and 16% (119,141 ha) as regeneration in 2010 (Fig. 2.4a).

The regenerating forests detected in 2010 were of different ages. Excluding areas younger than four years old, most of the regenerating forests detected in 2010 were 5–10 years old (53% or 5,900 ha), followed by forests in more advanced successional stages (17–22 years; 25% or 2,800 ha) and the intermediate forests (11–16 years; 21% or 2,300 ha). Values were similar for forests outside RAPPs with 51% (60,400 ha), 27% (32,500 ha) and 22% (26,100 ha) cover for each of the respective age classes (Fig. 2.4b).

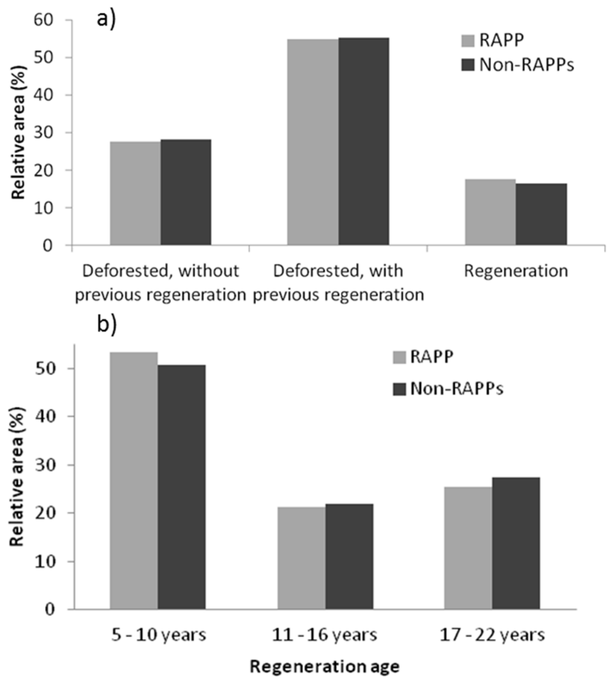

Figure 2.4. History of (a) deforestation and regeneration detected in 2010, inside and outside riparian permanent preservation areas (RAPPs) and (b) age of regeneration detected in 2010, inside and outside RAPPs in Paragominas.

2.4.3. RAPP environmental liabilities by land tenure

The RAPP environmental liabilities for 2010 were evaluated for each major type of land tenure in the region (CAR, agrarian reform settlements, indigenous lands and unregistered private lands) under the new Forest Code (Brazilian Federal Law N^o. 12.651, 25 March 2012) (Fig. 2.1c, Table 2.2). Each class of tenure presented a broadly comparable percentage of RAPP deforestation (as a percentage of number of landholding with RAPP), ranging from 80% (37 properties out of 46) for small properties (110–220 ha) to 93% (14 properties out of 15) for settlements (Table 2.2). In indigenous lands, small isolated areas were classified as deforested, but may actually be associated with naturally non-forest areas (such as sand banks).

Considering all types of land tenure, we found that c. 40% (52,383 ha) of the total RAPP area was in a deforested state in 2010. Large private properties account for 68% (35,718 ha) of the total deforested area, followed by unregistered private lands with about 17% (8,631 ha) and medium properties with 7% (3,588 ha). Under the new Brazilian Forest code, 94% (49,110 ha) of the total RAPP deforestation in Paragominas to date must be restored. This is less than 100%, as small properties need only restore 5–15 m wide RAPPs (36,186ha), depending on the size of the property. Agrarian reform settlements were considered as needing to restore 5-m wide RAPPs (542 ha) since most smallholdings were assumed to be smaller than this (Table 2.2; Supplementary information, Table S2.4).

Table 2.2. RAPP environmental liabilities detected in 2010 by land tenure (private properties registered in CAR, settlements, indigenous land and private but not registered lands), under the new Brazilian Forest Code (Brazilian Federal Law N° 12,651, from 25th March 2012), in Paragominas.

Land tenure types	Total area		Total RAPP		Deforested RAPP				RAPP to be restored	
	(ha)	(# of cases)	(ha)	(# of cases)	(# of cases)	(ha)	(%)[1]	(%)[2]	(ha)	(%)[3]
CAR										
small (≤55 ha)	5,308	217	344	110	100	217	63.0	0.4	36	16.7
small (55-110 ha)	6,552	81	556	68	61	269	48.3	0.5	72	26.7
small (110-220 ha)	8,289	52	628	46	37	371	59.1	0.7	186	50.0
medium (220-825 ha)	82,067	160	5,838	150	131	3,588	61.5	6.8	3,588	100.0
large (>825 ha)	1,329,427	448	84,336	448	398	35,718	42.4	68.2	35,718	100.0
Settlements	108,886	15	6,884	15	14	3,251	47.2	6.2	542	16.7
Indigenous land	97,789	2	5,831	2	2	338	5.8	0.6	338	100.0
Unregistered private lands	296,834	-	24,925	-	-	8,631	34.6	16.5	8,631	100.0
Total	**1,935,151**	**975**	**129,342**	**839**	**743**	**52,383**	**40.5**	**100.0**	**49,110**	**93.8**

[1] Proportion of deforested RAPP in this category.
[2] Contribution of this category to the total deforested RAPP.
[3] Proportion of deforested RAPP to be restored in this category.

2.5. Discussion

We found no evidence that riparian forests have been more effectively protected than non-riparian forests in Paragominas. The percentage of forest loss was, in fact, comparatively higher inside than outside RAPPs as recently as 2010, indicating a widespread lack of compliance with environmental legislation. This failure of compliance was further illustrated by a lack of evidence for higher levels of regeneration in riparian zones, where, according to the Brazilian Constitution (Article 225, §3°; http://english.tse.jus.br/arquivos/federal-constitution), property owners have been obliged since 1988 to restore areas that have been cleared illegally.

2.5.1. Deforestation of RAPPs in Paragominas (1988-2010)

There are similar deforestation patterns inside and outside RAPPS, with increasing deforestation until 2004 followed by a decrease from 2004 to 2010 that can be linked to government and civil society efforts to control deforestation in the Amazon generally, which started in 2004 and intensified after 2007 (Barreto and Araújo, 2012; Guimarães *et al.,* 2011). For example, in 2004, the Plan of Action for the Prevention and Control of Deforestation in the Amazon (PPCDAM) was launched (MMA, 2004), accompanied by an intensification of monitoring and enforcement activities by government agencies. In 2008, Paragominas began the 'Green Municipality' project and, in 2009, signed the Zero Deforestation Agreement (Frente Parlamentar Ambientalista, 2008) with the federal government. The Green Municipalities Programme of Pará State (Whately and Campanili, 2013) started in 2010, and Paragominas was the first municipality in Brazil to leave the deforestation Red List (Guimarães *et al.,* 2011; Viana *et al.,* 2012).

According to Brazilian Law (both the old and new version), only low impact activities (such as ecotourism) are allowed in riparian forests, with some amnesty in the updated Forest Code of 2012 allowing agrosilvopastoral systems in portion of APP areas deforested before July 2008 -hereafter termed 'consolidated APP'. Therefore, we expected that the proportion of RAPP forest cover would be higher and more stable throughout the study period compared to areas away from RAPPs where deforestation is partly allowed. However, deforestation of riparian forests followed the same general trend as deforestation elsewhere in Paragominas. Moreover, in relative terms deforestation was actually greater inside versus outside RAPPs in 2010. This finding may be because RAPPs are commonly cleared to provide access for animals (especially cattle) to water courses. Even when riparian forests remain, they are often accessible to cattle, resulting in damage from trampling, grazing and erosion (Kauffman and Krueger, 1984).

The geographical variability we observed in deforestation in different catchments in 2010 clearly demonstrates that clearance of RAPPs is related to the history of land-use change and occupation in the region. The colonization of Paragominas started with the opening of the Belém-Brasília highway (BR-010) in 1970 in the centre of the municipality, where we found the highest levels of RAPP clearance, and then spread to surrounding areas (Fig. 2.2). The north-east and south-west regions of the municipality are the best preserved today, with the latter being mainly occupied by a large certified forestry company, and the former being located partly in the Alto Rio Guamá indigenous reserve.

2.5.2. Regeneration of riparian forests

Under the new Brazilian law (Law N^{o}. 12.651, 25 March 2012), low impact activities in RAPPs are allowed. However, depending on the size of the private property, a deforested RAPP must be partly restored to at least 5m from the border of the waterway (Supplementary material, Table S2.4). Thus, in areas that have been cleared, forest regeneration may be expected to be proportionally higher inside RAPPs compared to elsewhere. However, the results show that regenerating forests represent only 18% of the total area mapped inside RAPPs as deforestation or regeneration in 2010, compared to 16% in non-RAPPs. Stages of forest succession detected in 2010 were also very similar for both RAPPs and non-RAPPs, being dominated primarily by younger forests (4–10 years old).

Forest regeneration may have increased in the region in the period 2011 to present, especially following the revision of the Forest Code in 2012. However, we do not believe this is the case, because interest and enthusiasm for new regeneration projects has stalled across Pará due to the lack of state regulations necessary to implement the federal legislation (including the Environmental Regulation Program and Environmental Reservation Quotas, abbreviated to PRA and CRA, respectively, in Portuguese), as well as delays in moving from the simple land registry (CAR) to the full property environmental license (LAR). In addition, regenerating forests <four years old cannot be readily distinguished from agricultural fallow areas (deforestation) in the satellite record, making it impossible to assess the extent of recent regeneration.

The latest version of the Forest Code only came into law in 2012 and it is therefore likely to be too early to measure its impacts on forest restoration in the Amazon, especially using moderate resolution imagery such as Landsat. However, as the Brazilian constitution requires environmental damage to be restored, the new Forest Code remains basically the same regarding the requirements for RAPP restoration in larger properties.

2.5.3. RAPP environmental liabilities by land tenure

When comparing different land tenure classes, larger properties (> 825 ha) contributed the most to the total area detected as deforestation in RAPPs in Paragominas in 2010, because they cover 69% of the total area of Paragominas. Conversely, small (≤ 55–220 ha) and medium (220–825 ha) properties, and settlements were the land tenure classes with the highest proportion of RAPP (relative to their total areas) in a deforested state in 2010 (mean 56.8%; small properties 61.5% and medium properties 47.2%). Thus, the planning and implementation of restoration activities need to focus on both large and small properties (Table 2.2).

The higher relative deforestation of RAPPs in smallholdings may be because subsistence farmers face much greater economic challenges in achieving legal compliance. Previous work has shown that many smallholders are unfamiliar with legal prescriptions of what comprises an APP, and where and how to restore areas that have been cleared (Sá, 2008; Sá *et al.,* 2008), as well as the kind of financial support potentially available to them (Cardoso, 2011). More generally, it is possible that RAPP restoration is not afforded high priority (compared to the restoration of legal protected areas) by many land owners, as the use of these areas for economic purposes is limited (for example, timber extraction is not allowed). Nevertheless, smallholder farmers in Paragominas encompass a diverse array of landowners, from traditional *ribeirinhos* to more recent colonist farmers and inhabitants of agrarian reform settlements; further research is needed to understand possible differences in compliance with environmental legislation among these groups.

2.5.4. Challenges and barriers to protecting and restoring riparian forests in the Brazilian Amazon

In order to mobilize and guide large-scale public policies for the restoration of riparian forests in the Brazilian Amazon, a number of challenges need to first be addressed. First, more accurate cartographic products are required to determine the extent of APPs (including RAPPs). The accuracy of APP maps in the Amazon is limited by the quality (or lack) of mapping data in the region, including high resolution and recent digital elevation models to inform improved hydrological models and quantification of the width of water courses (Silva *et al.,* 2013) and, critically, field validation data to establish whether water courses predicted by digital elevation models actually exist on the ground.

The RAPP mapping presented in this study is based on a 90-m resolution digital elevation model (DEM) of the space shuttle topographic mission (SRTM) from 2000 and refined using 5-m RapidEye images (which satisfy the mapping scale required by law). No ground-truthing was performed, and deforestation in RAPPs during the full time period was assessed using a 30-m spatial resolution (Landsat). Our mapping of RAPPs, and hence assessment of deforestation patterns, may be subject to both negative and positive biases. For example, our analysis may have overestimated the current distribution of water courses, as small streams predicted by this approach may only be dry topographic depressions on the ground. Small streams are also the most threatened by land-use change and forest loss (Iwata *et al.,* 2003; Biggs *et al.,* 2004), and it is hard to evaluate whether their absence from agricultural landscapes today means that they did not exist prior to recent deforestation (instead of being a natural phenomenon). Conversely, we may also have underestimated RAPPs, as the DEM resolution used in this study may have been insufficient to map smaller or transient streams that exist in the field but were not projected by the water courses mapping approach.

Addressing these problems is beyond the scope of this study, requiring higher resolution and more recent DEMs, historical information on stream extent and width, or the development of more realistic water course mapping approaches in undisturbed regions of the Amazon that can be extrapolated to human-modified areas such as Paragominas.

A second challenge, which compounds the problems of defining the extent and distribution of RAPPs, is a pervasive lack of clarity about what is legally considered to be a RAPP under Brazilian law. This, in turn, undermines confidence in defining the conservation and restoration responsibilities of a landowner in order to become compliant with the law. For example, it is unclear whether RAPPs should also be enforced in areas with irregular flows that may only contain water during severe storms or for a limited time in the peak of the wet season. Often these specific decisions are left to the subjective (and therefore variable and inconsistent) judgment of local environment agency enforcement officers.

A third major challenge is to improve the development of, and access to, reliable information on property boundaries and registration in the CAR system. The Secretary of State for the Environment (SEMAS) estimates that among 100,000 properties registered in CAR in the state of Pará, only 4,000 have been validated (the boundaries declared by property owners have been checked on the ground) (M. Ausier, personal communication 2013), indicating a serious lack of technical capacity in the state government. Moreover, even in Paragominas, 15% of the municipality is still composed of unregistered private lands (private properties that have not registered for CAR). This figure is much higher in other municipalities in the Amazon, and the spatial coverage of CAR remains very low in some places, such as Quatipuru (3%) and Augusto Corrêa (5%) (SEMA/Imazon, 2016).

A fourth challenge to implementing the restoration actions necessary to achieve environmental compliance is that land owners often do not have access to sufficient financial resources or technical support to implement the work. Where credit lines are available to support restoration activities (for example through PRONAF [Programa

Nacional de Fortalecimento da Agricultura Familiar] or Fundo Amazônia), individuals are often unaware that they exist, or how to access them (Cardoso, 2011). Other economic incentives, such as payment for ecosystem services (PES), are poorly established, partly as a consequence of the lack of federal governmental regulation of such incentives (Santos *et al.,* 2012). In situations where individuals are able to access credit, information on costs and technical assistance is often poor or non-existent, and the logistical support necessary to actually implement restoration is often lacking (such as provision of seeds, access to nurseries and technical support in planting efforts). Even in flagship areas such as Paragominas, there are only a few relatively small-scale restoration initiatives. As such, economic incentives and education program should be given greater priority over further command and control actions, especially if compliance is to be improved amongst more vulnerable smallholders (Brancalion *et al.,* 2012).

2.6. CONCLUSIONS

The legal protection given to riparian forests by Brazilian environmental law has not been sufficient to prevent them from being deforested in Paragominas, a flagship municipality for land-use sustainability in the Brazilian Amazon. By contrast, we found that deforestation inside riparian APPs was greater than deforestation outside RAPPs, even as recently as 2010. We also found that regeneration of deforested RAPP areas has fallen far short of what is needed for private properties to comply with legal requirements (whether prior to or after the revision of the federal Forest Code). Priority for restoration action must focus on larger properties because they account for most of the deforestation within RAPPs in Paragominas and across much of the Amazon. However, smaller properties, which include some of the poorest and most vulnerable people in the region, exhibit the highest relative rates of deforestation in RAPPs (deforestation as a proportion of total RAPP area), also require much greater attention, including the provision economic incentives and technical support on where and how to restore.

The development of more accurate maps of RAPPs and RAPP deforestation (combined with ground truthing of remotely sensed data) is an important first step in guiding efficient large-scale forest restoration action. Paragominas has seen some success in initial restoration projects and a major challenge remains in strengthening and up scaling these examples to other regions that have weaker levels of environmental governance.

Some of the issues we have discussed no longer present barriers to restoration in Paragominas (such as insufficient registration of properties in CAR) given the significant efforts made by civil society and government to remove the municipality from the Red List (Viana *et al.,* 2012). Initiatives like the Green Municipalities Programme (PMV in Portuguese), inspired by the experience of Paragominas, with their alliance of public, private and civil society partners, are improving compliance of private landowners, promoting forest restoration, reducing deforestation, and helping to improve clarity over land tenure. Although the birth of PMV has been heralded as conservation success story that marks a positive shift towards increased environmental conservation and awareness (Guimares *et al.,* 2011; Viana *et al.,* 2012), it is too soon to evaluate its success in achieving widespread compliance with Brazil´s environmental legislation.

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2.9. Supplementary Information

S2.9.1. Satellite imagery data

To cover the study area, 57 Landsat TM and ETM+ images, 30-metre spatial resolution, acquired between 1988 and 2010, were used (Table S2.1). The path/rows that cover Paragominas municipality are 223/62, 223/63, 222/62 and 222/63 (Table S2.1; Fig. 2.1). The images were acquired through the National Institute for Space Research (INPE, in Portuguese). In order to build the mosaic of RapidEye images, we acquired 55 orthorectified (3A level) scenes from 2009 (n=45) and 2010 (n=10), with a 5-metre spatial resolution (Table S2.2; Fig. 2.1a).

Table S2.1. Landsat TM/ETM+ data used to cover study area.

Year	223/62		223/63		222/62		222/63	
	Date	Sensor	Date	Sensor	Date	Sensor	Date	Sensor
1988	22/07/1988	TM	22/07/1988	TM	31/07/1988	TM	16/08/1988	TM
1990	28/07/1990	TM	25/05/1990	TM	-	-	-	-
1991	-	-	-	-	24/07/1991	TM	24/07/1991	TM
1992	02/08/1992	TM	02/08/1992	TM	-	-	-	-
1994	23/07/1994	TM	07/07/1994	TM	18/09/1994	TM	01/08/1994	TM
1995	-	-	-	-	-	-	-	-
1996	25/05/1996	TM	10/06/1996	TM	05/07/1996	TM	03/06/1996	TM
1997	-	-	-	-	-	-	-	-
1998	-	-	19/08/1998	-	28/08/1998	TM	28/08/1998	TM
1999	13/07/1999	ETM	-	-	-	-	-	-
2000	31/07/2000	ETM	31/07/2000	ETM	06/06/2000	ETM	06/06/2000	ETM
2001	-	-	-	-	-	-	-	-
2002	07/09/2002	ETM	-	-	28/06/2002	ETM	28/06/2002	ETM
2003	-	-	16/07/2003	TM	-	-	-	-
2004	15/05/2004	TM	15/05/2004	TM	15/10/2004	TM	09/06/2004	TM
2006	09/08/2006	TM	09/08/2006	TM	15/06/2006	TM	15/06/2006	TM
2008	14/08/2008	TM	29/07/2008	TM	20/06/2008	TM	20/06/2008	TM
2010	03/07/2010	TM	05/09/2010	TM	26/06/2010	TM	26/06/2010	TM

Table S2.2. RapidEye data used to cover study area.

Path/Row	Date	Path/Row	Date
2337901	05/09/2009	2337607	04/09/2009
2337902	05/09/2009	2237525	26/06/2010
2337905	02/08/2009	2237526	26/06/2010
2337906	03/08/2009	2237527	26/06/2010
2337907	04/09/2009	2237528	21/07/2009
2337908	14/08/2009	2337501	21/07/2009
2337801	21/07/2009	2337501	21/07/2009
2337802	21/07/2009	2337502	27/07/2009
2337803	02/08/2009	2337503	27/07/2009
2337804	02/08/2009	2337504	11/07/2009
2337805	27/07/2009	2337505	04/09/2009
2337806	04/09/2009	2237424	03/07/2009
2337807	14/08/2009	2237425	26/06/2010
2337701	21/07/2009	2237426	26/06/2010
2337702	21/07/2009	2237427	26/06/2010
2337703	02/07/2009	2237428	21/07/2009
2337704	27/07/2009	2337401	21/07/2009
2337705	27/07/2009	2337402	02/08/2009
2337706	04/09/2009	2337403	02/08/2009
2337707	13/06/2009	2337404	02/07/2009
2237627	20/08/2009	2337405	02/08/2009
2237628	21/07/2009	2237325	26/06/2010
2337601	21/07/2009	2237326	26/06/2010
2337602	21/07/2009	2237327	26/06/2010
2337603	02/07/2009	2237328	21/07/2009
2337604	27/07/2009	2337301	21/07/2009
2337605	27/07/2009	2337301	04/09/2010
2337606	04/09/2009	-	-

S2.9.2. Pre-processing

Landsat ETM+ images acquired in 2000 were georeferenced using control points extracted from GeoCover 2000 mosaic of NASA (National Aeronautics and Space Administration available at https://zulu.ssc.nasa.gov/MrSID/mrsid.pl). Images from other years were then registered based on the georeferenced images from 2000, using ENVI 4.7 software. Accurate georeferencing and registration is important to detect small scale changes over time. Both processes were based on the nearest-neighborhood resampling method, available in the Environment for Visualizing Images software - ENVI 4.7, using at least 40 image control points. The root-mean-squared-error (RMSE) maximum acceptable was 0.5 of a pixel.

The effects of haze and smoke were corrected in all images using a haze equalization algorithm (Carlotto, 1999). This method corrects the spectral bands in the visible region (1, 2 and 3) that are most affected by haze and smoke, using the bands that are free from this effect (4, 5 and 7). Then, images were radiometrically corrected using the calibration values (gains and offsets) of ETM+ (Chander *et al.*, 2009).

The images were then converted from radiance into absolute reflectance using FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) 4.7, the ENVI atmospheric correction module. The parameters of visibility and water vapor in the atmosphere were estimated from the reflectance of targets with known reflectance values (water and vegetation). The initial values of water vapor and atmospheric visibility to optimize the atmospheric correction model were 45 mm and 45 km, respectively.

S2.9.3. Spectral Mixture Analysis (SMA)

The next step was to estimate the abundance of pure components (pure pixels of vegetation - GV, bare soil, Non-Photosynthetic Vegetation - NPV, cloud and shade) at each pixel by applying the spectral mixture analysis (SMA) (Adams *et al.*, 1993) in the reflectance images. The SMA estimates the fraction of pure components in the image using the reflectance of each pixel, which is modeled by a linear combination of the reflectance product of the N pure components by their respective fractions, as shown in Equation 1:

$$R_b = \sum_{i=1}^{N} F_i R_{i,b} + \varepsilon_b \text{ for } \sum_{i=1}^{N} F_i = 1 \qquad (1)$$

Where, R_b is the reflectance measured in the band b; F_i is the fraction of component i; $R_{i,b}$ is the reflectance measured for the component i in band b; ε_b is the residual error for each band, which indicates the portions of the spectrum not modeled, and n is the number of bands (Roberts *et al.*, 1998). The error of the SMA is given by Equation 2:

$$RMS = (\sum_{b=1}^{N} \varepsilon_b^2 / n)^{1/2} \qquad (2)$$

The pure components GV, NPV and bare soil used to generate the SMA model were obtained from Souza Jr. *et al*. (2005) (generic pure components). The pure component of cloud was obtained afterwards and shade was calculated as a complement.

S2.9.4. Normalized Difference Fraction Index (NDFI)

Using fraction images obtained from SMA models, the NDFI (Souza Jr. *et al.*, 2005) was applied to the images to enhance the signal of forest degradation caused by logging and burning and can be computed by Equations (3) and (4):

$$NDFI = \frac{GV_{shade} - (NPV + Soil)}{GV_{shade} + NPV + Soil} \quad (3)$$

for,

$$GV_{shade} = \frac{GV}{100 - Shade} \quad (4)$$

Where, GV_{shade} is the shade-normalized vegetation fraction; *NPV* is the non-photosynthetic vegetation and *Soil* is the bare soils. This index is non-dimensional, ranging from -1 to +1 and the higher the value, the less degraded the forest is.

S2.9.5 Decision tree land cover classification

To perform the imagery processing steps - except georeferencing and atmospheric correction - a new software named ‘ImgTools’ was used. ImgTools is an intuitive software with a friendly user interface, developed in Interactive Data Language (IDL) platform and designed to automate the processing steps necessary to image classification (Souza Jr. and Siqueira, 2013).

Decision tree classification is a technique that uses a recursive partition of the data set, dividing it into smaller parts (Friedl and Brodley, 1997). The dividing process is performed by defining classification rules to each node in the tree. The basic elements that compose the tree are: rules, nodes, branches and classes. Additionally, the rules are composed of variable, operator and the optimal value to define the partitions. For this study the knowledge-based classification was performed, that is, the knowledge of the variables and the analyst interpretation were both used to classify images semiautomatically. The classification was performed to generate two main products: i) the distribution of forested and deforested areas for each year, and ii) a forest regeneration map. For the purposes of our analysis here, the class 'forest' encompassed undisturbed forests as well as degraded forests registered as having experienced some form of canopy disturbance (i.e. through logging or fire), but not outright deforestation.

The deforestation/degradation tree used NDFI and fraction images (GV, GV_{shade}, NPV, bare soil, and cloud) as tree variables. The decision tree was firstly applied to the baseline (initial state of land cover, at the first year of analysis) to classify non-forest (deforestation and natural non-forest areas), undegraded forest, regeneration, degradation, water and cloud. Then, the same tree, with adjusted decision rules values, was applied to the time series to detect land cover change over years, using non-forest from the baseline and accumulated deforestation as a mask, in order not to map these areas in the following years. Figure S2.1 shows the tree structure, including default values for each rule in the tree. The final set of decision rules values were based on knowledge of the analyst and can be adjusted according to his data interpretation (Souza Jr. *et al.*, 2013b; Souza Jr. and Siqueira, 2013; Gardner *et al.*, 2013).

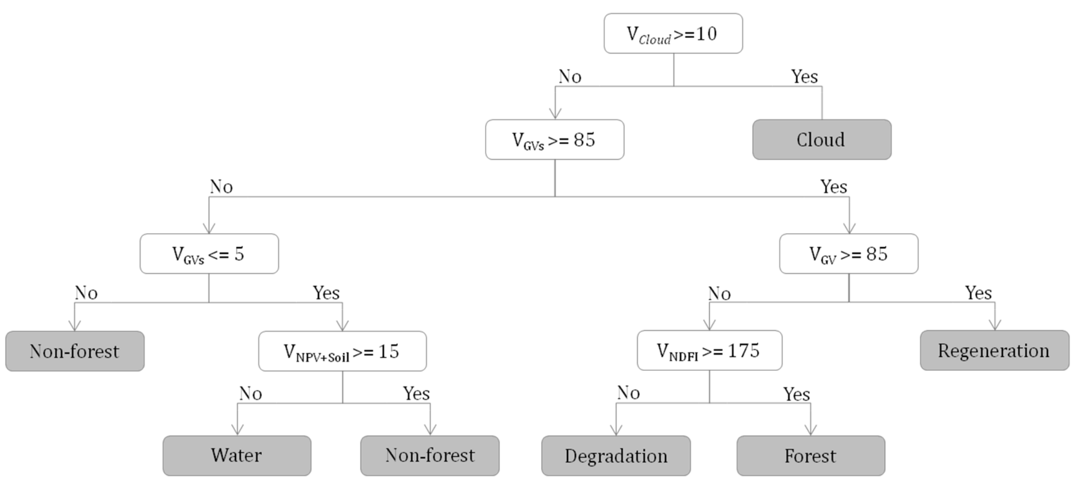

Figure S2.1. Deforestation and degradation decision tree structure used to perform classification. V referes to variables, numbers are default values for each rule in the tree. Note: If the year of analysis is not the baseline, then the classes Non-forest and Regeneration are called Deforestation (Souza Jr. *et al.*, 2013b).

Changes in forest cover prior to 2010 were assessed both across the municipality as a whole, and also within 190 third or fourth order hydrological micro-catchments (selected to be of approximately equal size – c. 5000 ha) to quantify geographical variability in deforestation patterns. Catchments boundaries were obtained in the ArcSWAT software using TopoData digital elevation model (30 m resolution) and were distributed in Paragominas across a forest gradient (6 to 100%) (Gardner *et al.*, 2013).

For forest regeneration analysis, a different classification tree was performed to detect regeneration process after deforestation events, regeneration detected in the baseline and new deforestation mapped over the time series (Fig. S2.2). The regeneration tree used fraction images (GV, NPV, bare soil, and cloud) as rule variables. An algorithm written in IDL was used to calculate the age of regeneration detected in 2010 (Siqueira, 2012). As a result, we had five classes, as it follows:

(i) regeneration - secondary forest younger than baseline (1988);

(ii) old-regeneration-regeneration: areas classified as secondary forest in the baseline and also mapped as secondary forest in the year of analysis, although they may have been mapped as deforestation between the baseline and year of analysis;

(iii) old-regeneration-deforestation: deforestation of secondary forests identified in the baseline;

(iv) non-forest: deforestation detected over years before the year of analysis plus natural non-forest areas;

(v) cloud.

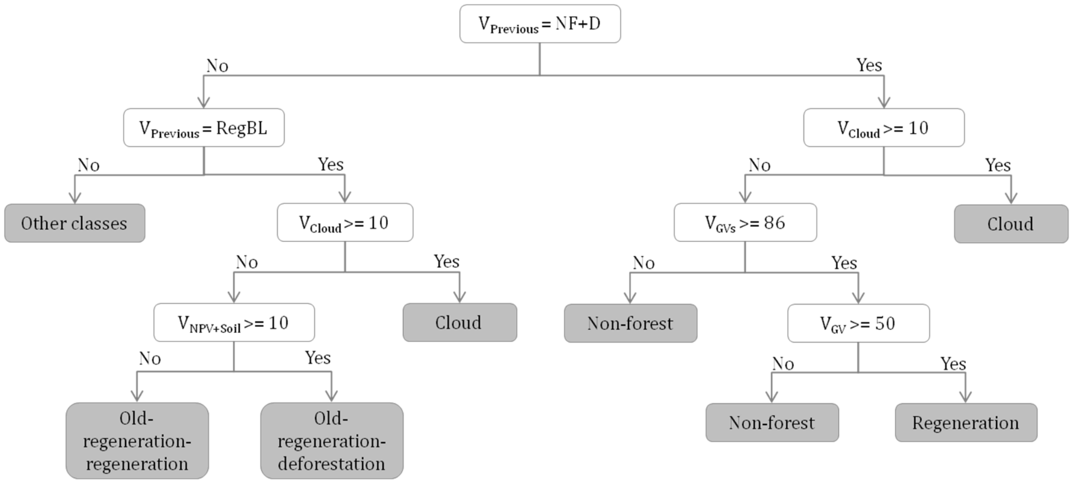

Figure S2.2. Regeneration decision tree structure used to perform classification. Where, V refers to variable; Vprevious is the classification before year of analysis; NF+D is the non-forest detected in the baseline + the accumulated deforestation detected until the year before analysis and RegBL is the regeneration detected in the baseline. Numbers are default values for each rule in the tree (Gardner *et al.*, 2013).

A spatial filter was used in order to eliminate classification errors (small groups of misclassified isolated pixels), reclassifying those pixels to the more abundant class in a 3x3 pixel neighborhood window. A temporal filter was also used to avoid some 'disallowed transitions' (Souza Jr. and Siqueira, 2013). For example, clouds detected in the year of analysis can be removed if mapped as forest in the year before and in the following year. Other combinations have also been implemented in order to reduce classification errors (Souza Jr. and Siqueira, 2013). To achieve a regular time interval data from 1988 to 2010, the deforestation from 1991, 1999 and 2003 was counted in the following year.

S2.9.6. Accuracy assessment of land cover mapping

In order to validate the Landsat classification described in the previous section, we performed an accuracy assessment of Paragominas land cover map for 2010, using 55 RapidEye high-resolution images (5 metres - Table S2.2) as reference data. Whilst it would be ideal to validate land cover map for all years, extrapolating an accuracy assessment for one focal year to the full time-series being assessed in a given study is generally accepted as standard procedure in the remote sensing community, since we used a normalized time-series of Landsat imagery and applied the same image classification algorithm to entire data set. For this purpose, we applied the methodology developed by (Powell *et al.*, 2004) with adaptations for this study.

The pixels distribution followed the cluster sampling method, in which a pivot pixel is randomly positioned and four companion pixels are systematically positioned around the first one, creating the cluster. Each pixel of the cluster was treated as an independent sample. A total of 260 pivot pixels were randomly distributed in the study area to ensure that the samples were representative of the municipality and each land cover class. Thus, considering the cluster sampling, a total of 1300 pixels sample were evaluated to validate land cover map from 2010: 200 for forest, 400 for degradation, 250 for deforestation and 450 for regeneration class. In order to reduce uncertainties and confusion among classes, forest and degradation were evaluated as a single class called 'forest' – which was the class used for the main analyses in the paper. Clouds, shade, water, mixed and no data pixels were excluded from the analysis. We used stratified sampling to ensure that our results were representative both inside and outside RAPPs.

Two trained analysts evaluated each selected pixel to determine whether the result of the classification corresponds to the same land cover class observed in the high resolution image. The final decision about the land cover for each pixel is made considering the highest number of votes at the end of the evaluation between the two analysts. This final decision is used as reference value in the accuracy assessment. The final sample used to calculate overall accuracy was obtained after corrections of the reference data (geocorrections, edges and different dates between reference and map, called change pixels) to eliminate errors in the processing. The accuracy of the classifier was assessed using a confusion matrix (Story and Congalton, 1986).

S2.9.7. Riparian areas of permanent preservation (RAPP) mapping

We used a procedure to map water courses based on a Digital elevation model (DEM) product refined with 5-metre RapidEye images and a knowledge-based classification to map land cover changes in eastern Amazon, using a software designed to automate the processing steps necessary to image classification (Souza Jr. and Siqueira, 2013). Both products were combined in order to assess RAPPs loss over time.

For this study, we considered only RAPPs from streams, rivers and water bodies (lakes and dams), excluding the other types of APPs (e.g. headwaters, mangrove, sand dune vegetation, high declivity areas - > 45°). First, we used the 90m-resolution Digital Elevation Model (DEM) of Space Shuttle Topographic Mission (SRTM) in order to map rivers automatically, based on the SRTM elevation data, using ArcGIS 10.0.

Second, we performed a fusion between the SRTM and the 5-metre RapidEye images from 2009 and 2010 to create an anaglyph product using the software ERDAS Anaglyph tool. RapidEye images satisfy the mapping scale required by law (1:50.000) (Souza Jr. *et al.*, 2013a). In order to correct possible mistakes found in the linear features mapped automatically (streams and rivers), we combined the features to the anaglyph product and performed a visual analysis using ArcGIS. The visual analysis was facilitated by using 3D glasses to have a better perception of the three dimensional relief (Souza Jr. *et al.*, 2013a). Lakes and dams were manually mapped using Landsat images from 2010, at a 1:50.000 scale.

The third step was to map the RAPPs around the streams, rivers, lakes and dams, according to Brazilian environmental law. RAPPs around streams and rivers were calculated under the previous Brazilian Forest Code requirements (Brazilian Federal Law Nº 4.771, from 15th September 1965), since our goal is to assess how legislation affected riparian forest protection in the past two decades (1988 to 2010) (Table S2.3). All streams and rivers mapped in this study were considered to be subject to enforcement as defined by Brazilian law. However, there remains considerable uncertainty as to what regulating authorities actually define as a RAPP in practice and for a given place, particularly in areas where water flows may have been altered due to historical land-use change and in areas where water flow may temporarily cease (perhaps naturally) during particularly dry periods. The variable width along the same water course was not taken into account in this study.

Table S2.3. Buffers radius around rivers, streams, lakes and dams used to map RAPP in Paragominas, based on Brazilian legislation (Law Nº 4.771, from 15th September 1965).

Water courses	Water course width	RAPP width
Rivers and streams	< 10 m wide	30 m
	10-50 m wide	50 m
	50-200 m wide	100 m
Lakes	< 1 ha	-
	1-20 ha	50 m
	> 20 ha	100 m
Dams	< 1 ha	-
	1-20 ha	15 m

Approximately 95% of the water courses mapped were less than 10m in width; 3% were 10 to 50m in width and 2% were 50 to 200m. RAPPs from streams, rivers, lakes and dams were joined into a single shape file, which was then combined with the classification products (deforestation and regeneration), using ArcGIS 10.0, in order to describe patterns of RAPP loss over time and the history of regeneration. The class 'water' detected in RAPPs was removed from the analysis, since protection area includes only the marginal area of the water courses and water bodies.

S2.9.8. Current RAPP environmental liabilities by land tenure

The first step to obtain the environmental license for economic activities is for land owners to provide the state government a digital geodatabase (CAR) of their properties. This register must inform the land cover, including APP (Guimarães *et al.*, 2011). In order to calculate RAPP environmental liabilities, we used Landsat classification from 2010 and divided Paragominas into four main categories of land tenure: CAR from February 2013 (small, medium and large private properties – 74% of the municipality) provided by the State Secretary for the Environment (SEMAS), agrarian settlements (agricultural families placed in rural lands by the Brazilian Colonization and Land Reform Agency – 6%), indigenous land (5%) and unregistered private lands (private untitled lands - 15%) (Fig. 2.1c).

According to the new Brazilian Forest code areas deforested up to 22nd July 2008 are termed 'consolidated rural areas', and RAPPs do not need to be fully restored. The

RAPP width to be restored depends on the private property sizes and the water course types (Table S2.4). In order to estimate environmental liabilities in RAPPs, we considered all the deforestation in RAPPs detected in smallholder properties (<= 220 ha) and agrarian settlements as being from 'consolidated areas' (areas deforested before 22nd July 2008) – meaning that the landowner would not need to recover the entire RAPP according to Brazilian environmental law. By contrast, it was assumed that RAPPs from medium and large properties (> 220 ha), unregistered private lands and indigenous lands would need to be fully restored (Table S2.4).

Table S2.4. RAPP forest restoration requirements under the new Brazilian Forest Code (Law N° 12,651, from 25th March 2012), for private properties in Paragominas.

Water courses	Private property sizes	RAPP width to be restored
Rivers and lakes	≤ 55 ha	5 m
	> 55 ha and ≤ 110 ha	8 m
	> 110 ha and ≤ 220 ha	15 m
	> 220	min. 20 m to max. 100 m[1]
Lakes	> 220	30 m
Dams	-	15m

[1] Depending on the Environmental Regulation Program (PRA, in Portuguese) of the property.

Property sizes registered in CAR were defined according to the Federal Law n° 8.629, from 25th February, 1993, as small (≤ 220 ha), medium (> 220 ha and ≤ 825 ha) and large properties (> 825 ha).

S2.9.9. Accuracy assessment of land cover mapping

The overall accuracy for mapping forest (under varying levels of degradation), deforestation and regeneration was 0.89 using RapidEye 5-metre resolution imagery as reference data. The user's accuracy for forest, regeneration and deforestation was 0.84, 0.92 and 0.96, respectively (Table S2.5). The overall accuracy ranged from 0.78 with no correction to 0.89 when all reference data corrections were applied (Table S2.6). The total of number of excluded samples pixels, including correction, water, cloud/shade and mixed pixels, was 249 (Table S2.7). The lower accuracy for the forest class can be explained by the fact that degraded and un-degraded forest were evaluated as a single class. However, the estimates of degradation and deforestation are susceptible to significant uncertainty, since severe forest degradation can commonly be confused with deforestation during classification processes (Souza Jr. *et al.*, 2013b). That said, both 'undegraded' and 'degraded' forest were pooled for the purposes of our analysis into 'forest' so this uncertainty does not affect our results.

Table S2.5. Accuracy assessment of the Landsat classification results using high spatial resolution RapidEye data as a reference.

Land cover classes	Reference data			Row total	User's Accuracy
	Forest (forest + degradation)	Regeneration	Deforestation		
Forest (forest + degradation)	424	10	72	506	0.84
Regeneration	15	188	2	205	0.92
Deforestation	6	6	328	340	0.96
Columm total	445	204	402	1051	-
Producer's Accuracy	0.95	0.92	0.82	-	-
Overall accuracy = 0.89					

Table S2.6. The impact of applying corrections to the reference data on the accuracy assessment of the Landsat classification results.

Version	Correction to reference data set	Number of samples	% Overall agreement
1	None	1199	0.78
2	Geocorrection	1167	0.81
3	Map edge	1143	0.82
5	Change pixel	1051	0.89

Table S2.7. Total number of excluded sample pixels from the accuracy assessment of the Landsat classification.

Reason for exclusion	# of samples	%
No data	2	0,8
Geocorrection	32	12,9
Map edge	24	9,6
Mixed pixel	3	1,2
Change pixel	92	36,9
Cloud/shade	81	32,5
Water	15	6,0
Total	249	100,0

S2.9.10. Supplementary References

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Chapter 3

3. Compensating for past deforestation: assessing the legal forest surplus and deficit of the state of Pará, eastern Amazonia

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Compensating for past deforestation: assessing the legal forest surplus and deficit of the state of Pará, eastern Amazonia

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3.1. Abstract

Up to 80% of each private rural property in the Brazilian Amazon is protected by law through the Legal Reserve (LR) mechanism of the federal Forest Code, underlining the conservation importance of forests on private lands in one of the world´s most important biomes. However, our understanding of the discrepancies in levels of forest protection on private lands as obligated by the law versus what occurs in practice remains very poor. We assessed patterns of forest cover and legal compliance with the Forest Code in the 1.25 Mkm^2 Brazilian state of Pará, which has the highest deforestation rate in the Amazon. We evaluate the LR deficit and surplus patterns for different sized properties and across 144 municipalities, and found that the total LR surplus (12.6 Mha) was more than five times the total area of deficit (2.3 Mha). Yet, from the total surplus, only 11% can be legally deforested while the remaining 89% is already protected by law but can be used (sold or rented) to compensate for areas that are under deficit. Medium and large-scale properties make up most of the total LR deficit area, while agrarian reform settlements had comparatively large amounts of both compensation-only surplus and deforestable surplus. Most of the municipalities (77%) in the state could compensate their total deficit with surplus areas of LR in the same municipality, while the reminder can compensate their deficit in one or more neighboring municipalities, indicating compensation can always take place close to the source of the deficit. Maximising the environmental benefits of achieving Forest Code compliance requires measures that go beyond the existing legal framework, including interventions to avoid further deforestation in places where it is still legal, compensate in close proximity to areas with legal reserve deficit and promote local restoration on degraded lands.

Keywords: Forest restoration; Rural properties; Remote Sensing; Brazilian environmental policy; Legal Reserve; Spatial planning

3.2. Introduction

Native vegetation covers about 60% of the national territory of Brazil, with 40% under some form of public protected area (conservation areas in the public domain and indigenous lands) and the remaining 60% located in private areas (e.g. Legal Reserves and riparian forests) or public lands with no clear designation (Ferreira *et al.*, 2012; Soares-Filho, 2013). The protection of forests on private land is therefore a vital part of any overall conservation strategy, helping sustain the delivery of critical ecosystem services, including maintenance of hydrological cycles, water quality, climate regulation through carbon sequestration and storage and the conservation of biodiversity (Daily *et al.*, 1997; Nasi *et al.*, 2002; Grimaldi *et al.*, 2014).

In Brazil, the conservation of forest on private lands is primarily regulated by the Brazilian Environmental Law (Law N° 12.651, 25 March 2012) (Brazilian Federal Government, 2012b), commonly known as the Forest Code. This regulation divides rural properties into two areas: land for production and land dedicated to conservation and the sustainable management of natural resources. The latter is divided into two further categories: (i) permanent preservation areas (APP, in Portuguese) to protect particularly sensitive areas such as riparian vegetation, springs, steep slopes (>45°) and hilltops, where only low impact activities, such as ecotourism, are allowed; and (ii) Legal Reserves (LR) to promote the sustainable use of natural resources and the conservation of biodiversity. Economic activities, such as forest management for selective logging, are permitted in LRs under license but deforestation is not allowed. According to the updated Forest Code, last revised in October 2012, the definition of the LR area in a rural property is based on the Brazilian region where the property is located (e.g. LR is up to 80% in the Legal Amazon but only 20% in the other regions), the type of native vegetation (forest or savanna), the size of the property, region-specific regulations where LR reductions are allowed (e.g. areas that are zoned for agricultural development under state zoning plans) and the timing of deforestation (Brazilian Federal Government, 2012b).

Once the required LR area has been defined for each rural property, it is possible to estimate both the LR deficit, which is the shortfall of forest cover that is required to comply with the law, and the potential surplus, which is the forest cover additional to that required by law, expressed as a percentage of the total property area. The total surplus can also be disaggregated into that which is in excess of the LR requirement but which nevertheless cannot be deforested, yet can be used to compensate properties that are in deficit (termed here compensation-only surplus), and that which is in excess of the LR requirement but which can legally be deforested (i.e. for the Amazon biome areas of forest that are in excess of 80% of each property area, termed here deforestable surplus) (Figure 3.2). This distinction is of critical importance as the deforestable surplus is the only surplus that offers genuinely additional benefits for forest conservation (i.e. it is at risk of being cleared if not used to compensate properties with a LR deficit), whilst the compensation-only surplus is an important mechanism for providing monetary compensation to law-abiding landowners who did not deforest in the past.

In order to offset the LR deficit, the updated Forest Code provides two possibilities: forest restoration within the same farm that has the deficit, or compensation of LR deficit by acquiring, either by rent or purchase, the surplus of properties elsewhere. With the exception of APP areas this means that landowners can maintain their LR outside the boundaries of the farm that is in deficit without needing to retire land from production for restoration purposes. Trading for LR compensation can occur through mechanisms such as Environmental Reserve Quotas (CRA) and conservation easements (Brazilian Federal Government, 2012b; Zakia and Pinto, 2013), with an increasing number of initiatives seeking to facilitate such exchanges (such as the online legal reserve market place offered by *Bolsa Verde Rio*: www.bvrio.org).

However, land tenure uncertainties, e.g. land ownership rights and location of properties, make it difficult to conduct an accurate assessment of land cover in rural properties or implement environmental legislation effectively (Barreto *et al.*, 2008; Brito and Barreto, 2011). To address this, the Brazilian government created the Environmental Rural Property Register (CAR, in Portuguese, first introduced in the state of Pará in 2006), a mandatory georeferenced register of private properties, that has been instrumental in helping to both assess and promote compliance with environmental regulations, curb deforestation and foster more effective economic and environmental planning. The updated Forest Code states that by the 5th of May 2016, all rural properties in the country must be registered in CAR (Brazilian Federal Government, 2012b, 2012a).

Despite Brazil having some of the world´s most stringent environmental regulations for the legal protection of native vegetation in private properties, the extent of private reserve surpluses and deficits has hitherto been very poorly assessed, and never at the scale of an entire state. Although Soares-Filho et al. (2014) assessed compliance with the Forest Code at the scale of the entire country, a lack of data on property boundaries meant that they used micro-catchments as their unit of analysis. The lack of more detailed assessments can be explained by: (i) the historic lack of a minimally accurate and representative georeferenced register of private properties for any Brazilian state – a task further hampered by insufficient technical expertise within state governments to validate CARs declared by property owners themselves; (ii) a lack of detailed and reliable Geographic Information Systems (GIS) and remote sensing products, especially for the Amazon region – including water course mapping at a 1:50.000 scale as required by law (Souza Jr. *et al.*, 2013a) and land cover maps with a resolution consistent with the scale of individual properties; and (iii) the complexity of Brazilian environmental laws that have led to uncertainty, misunderstandings and controversies among different sectors (e.g. government, NGOs and farmers) on how to apply regulations and estimate legal liabilities (Ellinger and Barreto, 2012; Vale *et al.*, 2014; Vieira *et al.*, 2014). Taken together, these barriers have undermined effective law enforcement, compliance monitoring and more sustainable land-use planning of private properties.

Here we estimate the total LR deficit and surplus for the state of Pará, which covers around 25% of the Brazilian Amazon, and compare levels among different sized properties and across 144 municipalities. We focus on Pará, the second largest state in Brazil, because: (i) it is the most advanced state in the Amazon in registering its private rural properties in the CAR system; > 60% of the area suitable for registry was included in the state government database by 2014; (ii) it currently has one of the highest rates of deforestation in the Amazon: an average of 2,000 km^2/year from 2011 to 2015, compared to 5,500 km^2/year for the whole Brazilian Amazon, and (iii) state and municipal governments of Pará, together with civil society, have been particularly active in their efforts, to reduce deforestation and the state has been recognized as setting an example for other parts of the Amazon, eg. through Para´s Green County initiative. We address four specific questions: (i) What is the LR deficit and surplus for the entire state of Pará?; (ii) What proportion of the total surplus can be considered deforestable versus compensation-only surplus? (iii) How is the total deficit and surplus for the state distributed across properties of different sizes?; and (iv) What is the capacity of each municipality to compensate its LR deficit within the same or adjacent municipalities?

3.3. METHODS

3.3.1. Study area

Our analysis is focused on the state of Pará, located in the eastern Brazilian Amazon (Fig. 3.1). Pará is the second largest state in Brazil, larger than many countries (e.g. Peru, South Africa) and intersects five of the key areas of endemism in the Amazon. It has an estimated population of 8 million people, with an area of 1.25 million km^2, encompassing 144 municipalities and with a Gross Domestic Product of R$ 88.3 billion (IBGE - Brazilian Institute of Geography and Statistics, 2014), mostly from the extractive industry (e.g. iron, bauxite, wood, charcoal), agriculture (e.g. palm oil and cassava) and cattle ranching (Pará has the fifth largest cattle herd in Brazil – with 17 million heads in the 2013 census) (IBGE - Brazilian Institute of Geography and Statistics, 2013).

Pará has about 55% of its territory, or 685,575 km^2, protected by law in sustainable-use, strictly protected, or indigenous reserves (Brazilian Ministry of the Environment and National Indian Foundation, 2013). However, it also had one of the highest rates of deforestation in the Amazon, which is related to the pattern of recent occupation and agricultural expansion incentivized by the construction of highways, the development of large-scale industries, such as energy and mining, and the expansion of agriculture and cattle ranching (Whately and Campanili, 2013). In response to this, the Federal government launched a major program in 2004 to combat deforestation in the Amazon, the Action Plan for Prevention and Control of the Legal Amazon Deforestation

(PPCDAm in Portuguese), which encompassed a set of command, control and monitoring measures, as well as large-scale reserve expansion. These measures helped reduce deforestation across the biome by more than 80% from 2004 to 2012 (MMA - Brazilian Ministry of the Environment, 2004a; Whately and Campanili, 2013). In this context, the State Government of Pará also launched the Green Municipalities Program in 2011 in partnership with municipalities, civil society, private initiatives and the Public Prosecution Service.

One of the main goals of the Green Municipalities Program is to control deforestation by increasing the property area registered under the CAR system. According to the program, Pará had more than 60% of its private land registered in the CAR system by 2014 (Green Municipalities Program, 2014). However, the tenure situation of private land across Pará remains in a confused state, with 39% of the territory - mainly the eastern portion - presenting tenure irregularities. The remaining 61% that has defined tenure includes protected areas, agrarian reform settlements and registered properties.

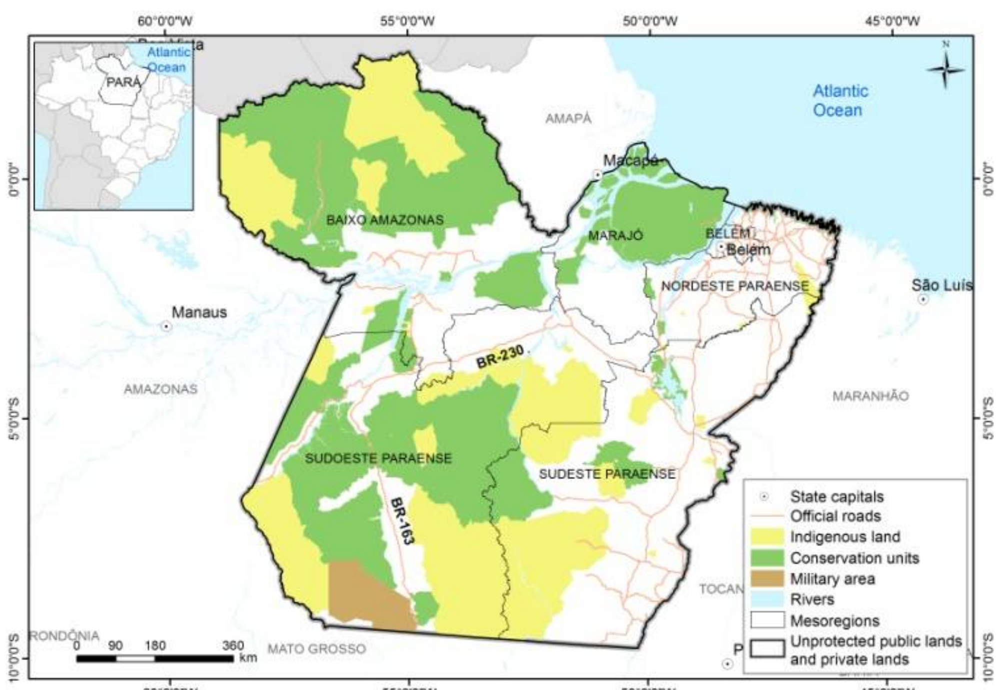

Figure 3.1. Study area, state of Pará, located in the Brazilian Amazon, northern Brazil.

3.3.2. Accounting for Legal Reserve deficit and surplus

We analyzed approximately 57,890 properties registered in the CAR system and 945 agrarian reform settlements (set of small rural properties created by the Rural Settlement and Agrarian Reform – INCRA – for low income families), amounting to 58,835 registered areas. We excluded all protected areas from this analysis as our focus is on compliance in private lands. Estimating LR deficit and surplus in Pará required us to reduce the overlap between geographic databases, define the LR percentage for each property, and estimate LR deficit and different types of surplus for each property (Fig. 3.2). We then used this to estimate the LR balance across the state of Pará and within all municipalities based on the Brazilian Forest Code regulations. These analytical steps are summarized in Figure 3, and described in detail below.

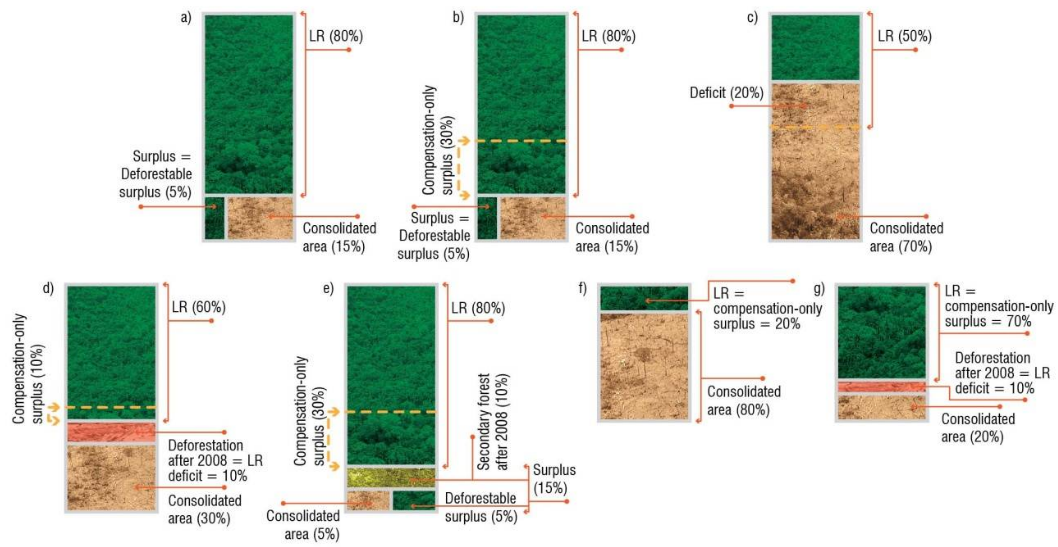

Figure 3.2. Examples of LR deficit and different types of surplus per private property based on the updated Forest Code definitions: a) deforestable surplus for both medium/large properties located where LR reduction is not allowed. The minimum LR permitted is 80% of each property and only areas of forest in excess of this percentage can be deforested; b) compensation-only surplus and deforestable surplus for medium/large properties located in situations where LR reduction is allowed. Forest cover from 50%-80% cannot be deforested but can be used for compensation in medium/large properties and forest cover above 80% can be deforested; c) LR deficit where LR reduction is allowed. The land owner must restore forest up to 50% of the property; d) deficit (deforestation after 2008) and compensation-only surplus for medium/large properties located in situations where LR reduction is allowed; e) compensation-only surplus and total surplus for medium/large properties where reduction is allowed; f) compensation-only surplus for small properties that is the same as the RL and g) deficit (deforestation after 2008) and compensation-only surplus for small properties which again is the same as the LR.

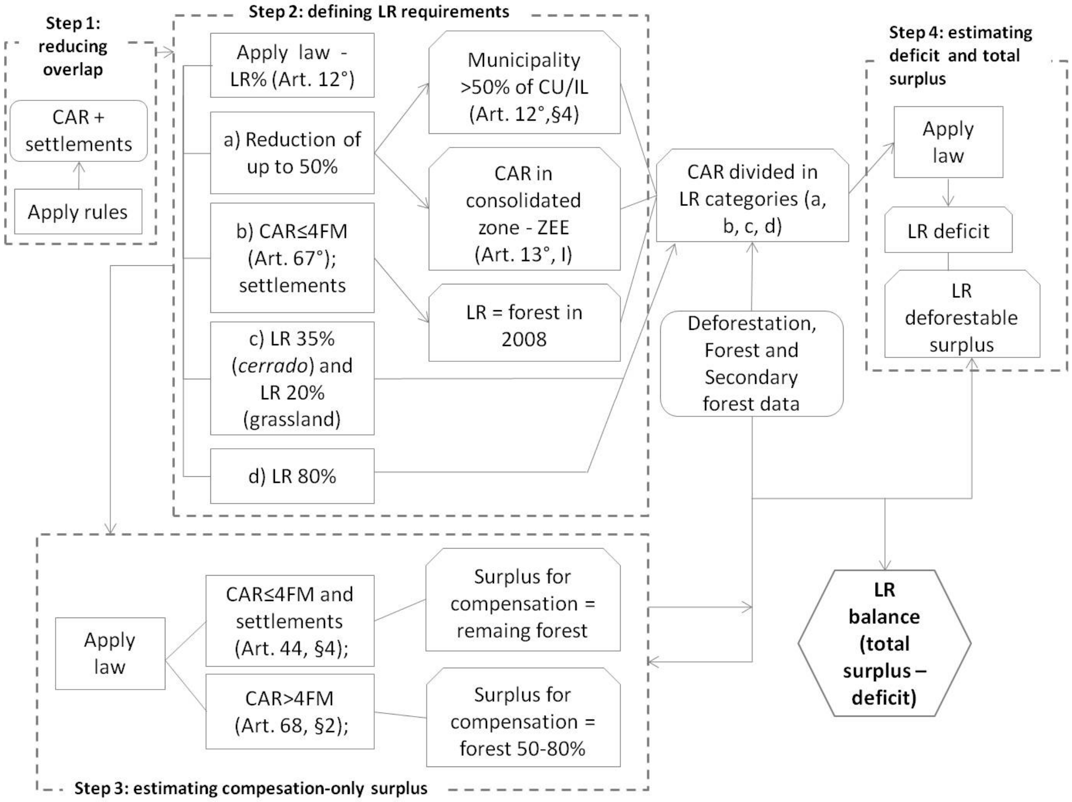

Figure 3.3. Summary of the methodology applied to estimate deficit and surplus of Legal Reserve in private properties in the state of Pará. The definition of the Legal Reserve percentage was based on four main criteria: (a) reduction of up to 50% for properties located in specific regions; (b) LR for properties up to 4 fiscal modules (FM) and settlements; (c) LR of 35% or 20% for non-forest vegetation areas (*cerrado* and grassland, respectively) and (d) LR of 80% for all properties where the other specific rules do not apply. LR stands for Legal Reserve; CAR - Environmental Rural Property Register; CU – Conservation Units; IL – Indigenous Land and ZEE - Ecological and Economic Zoning plan.

3.3.3. Reducing overlap between properties registered in CAR

The property database used in this study is restricted to the areas that can be registered in CAR, and therefore excludes indigenous lands, conservation units (except Areas of Environmental Preservation – APA, in Portuguese, where production land-uses are permitted), military lands and water bodies. The first phase of registering a private property in the CAR system involves contributing to a temporary registration (called a "provisional CAR") that is then validated by the state government (when it then becomes a "definitive CAR"). However, due to the lack of technical capacity and accurate base maps, only a small portion (1%) of the CARs for the state of Pará, and the country more generally, have been validated (State Environmental Secretary, 2015). As a result there are a large number of errors and disputes over farm boundaries. Reducing the overlap between rural properties in the temporary CAR was therefore the first step towards obtaining more precise information regarding the Legal Reserve deficit and surplus for the state. We estimated an initial total overlap of 6.8 Mha, that is, 24% of the total area that is registered under the CAR. To reduce the area of overlap in farm boundaries we adopted the following criteria:

a) Where properties have the same CAR code, the most recent entry was considered because there may be more than one version of the same property in the database;

b) Where there was an overlap greater than 5% between an approved CAR and a provisional CAR issued before the former's approval, the property with the provisional CAR was excluded; No properties were excluded where the overlap was less than 5% (allowed by law);

c) Where overlap was greater than 80%, the smallest property was excluded;

d) Where properties were obviously duplicated in the system (i.e. they occupied exactly the same area and had exactly the same size), one of them was excluded at random;

e) Properties with an overlap larger than 30% with agrarian reform settlements were excluded;

f) Properties that overlapped more than 50% with water bodies were excluded, in addition to those that were located more than 50% in areas not suitable for registry (areas where CAR is not permitted). For example, properties located in Indigenous lands.

These criteria were combined into an algorithm developed in ArcGIS Python 2.7 and, after being applied to the CAR database, the overlap decreased to 667,000 ha - a reduction of 90% (6 Mha) compared to the initial total overlap.

3.3.4. Defining Legal Reserve according to the updated Brazilian Forest Code

A set of regulations present in the Brazilian Forest Code define the percentage of LR in rural properties (Fig. 3.2 and 3.3; see Tables S3.2 and S3.3 for a summary). In general, rural properties with forest areas located in the Brazilian Amazon must have a LR of 80% of each property's total area. However, there are several conditions that allow reduction of this initial percentage for forest restoration or compensation purposes (not deforestation) (Table S3.3). It means that the only portion that can be deforested is that in excess of 80% forest cover in a given property. However, properties that deforested more than 50% in the past must restore or compensate back up to 50%, not 80%. The rules applied to define LR were:

a) *Areas with a possible reduction of up to 50% of the Legal Reserve in the property area*: according to Art. 12, § 4, the minimum LR requirement can be reduced from 80 down to a minimum of 50% of each property area (for restoration purposes) when the municipality in which the property is located has more than 50% of its area protected by public Conservation Units (CUs, excluding APAs that may be occupied by private lands) and/or Indigenous Lands (ILs) (Fig. S3.1). The LR can also be reduced down to a minimum of 50% of the area of each property (exclusively for regularization whether through on-farm restoration or off-farm compensation) when properties are located in areas designated for agricultural activities, and as indicated in the Ecological and Economic Zoning plan of the State (Art. 13, I). In order to comply with this regulation, we distinguished whether properties were located within the consolidated areas of the Ecological and Economic Zoning plan developed by the state Environmental Secretary (SEMAS-PA), excluding water resource areas, and identifying consolidated areas (areas deforested before 22nd July 2008) inside this zone.

b) *Legal Reserve for properties smaller than four fiscal modules on 22nd July 2008*: A Fiscal Module (FM) is a Brazilian government agrarian measurement that represents the minimum area of an economically feasible rural property. One Fiscal Module ranges from 5 to 110 ha, depending on the municipality (Landau *et al.*, 2012). For rural properties that have an area of up to four fiscal modules on 22nd July 2008 the LR is defined as the area under native vegetation as of 22nd July 2008 (Art. 67), thereby providing an amnesty for many smallholders who would otherwise have to restore or compensate for historical deforestation (Soares-Filho *et al.*, 2014). In this case we selected current properties with up to four fiscal modules, since there is no CAR data for 2008, and compared them with the current forest cover to verify the percentage of native vegetation for each property. Those with deficits were then crossed with the forest cover of 2008 to determine the properties current LR requirement. The same criteria were used for rural settlements as they are largely dominated by small holdings of standard size.

c) *Legal Reserve for vegetation other than forest:* according to Art. 12, item I, *cerrado* vegetation and grassland areas in the Brazilian Amazon have a LR requirement of 35% and 20%, respectively, of the total property area. It was not possible to account for the deficit or surplus of these two vegetation types because PRODES (Brazil´s Federal government deforestation monitoring program for the Amazon) data do not include deforestation in *cerrado* and grassland areas, which is much harder to detect. The total area of *cerrado* or grassland mapped by PRODES was 1.8Mha or 8% of the total CAR analyzed area. We considered properties with *cerrado* or grassland areas larger than 50% of the property area as neutral (no deficit or surplus), to reduce the risk of bias. For those with less than 50% of *cerrado* or grassland we assumed that they were forested and applied the other criteria accordingly.

d) *Legal Reserve in remaining areas:* rural properties that were not eligible for any of the reduction conditions described above had their LR percentage defined as 80% of each property area, according to the default LR requirement for the Amazon biome as established in the updated Brazilian Forest Code.

Deforestation data used to estimate LR deficit is based on the cumulative PRODES up to 2012 less the area of secondary forest detected by TerraClass (Brazil´s federal government land-use monitoring project for the Amazon) in the same area. The total forest area is the sum of forest detected by PRODES with the secondary forest detected by TerraClass (forest at advanced stage of regeneration) in areas previously detected as deforestation by PRODES. Deficits in APPs were not accounted for in this study due to the lack of a more detailed and reliable hydrography mapping (1:50.000) at the scale of Pará, required by Decree N° 7.830, 17 October 2012 for the National CAR System.

3.3.5. Estimating compensation-only surplus and defining types of surplus

We considered the following regulations of the Forest Code to estimate the surplus that is available for deficit compensation only (i.e. areas of forest that cannot be deforested): (i) for small properties or family holdings, any remaining native vegetation area under 80% of each property is considered as compensation-only surplus (Art. 44, §4); (ii) for medium and large properties that have forest cover greater than 50% and less than 80%, this range of forest cover is considered a compensation-only surplus where LR reduction is allowed (Art. 68, §2) (Fig. 3.2, 3.3; Table S3.2).

The number of opportunities provided by the Forest Code to compensate LR deficit makes it possible for properties to present, at the same time, a deficit (e.g. deforestation of native forest within LR after 22nd July 2008) and surplus for compensation (compensation-only surplus). For example, for the cases where LR reductions are allowed, a large property with 70% of forest cover in 2008, but where the landowner deforested an area of 10% after 2008, would present a LR deficit of 10%. But at the same time, the property presents a LR surplus of 10% that would be available to compensate the deficit of other properties, if the area is not embargoed, since forest cover of 50-80% of the property can be used to compensate LR deficit (Table S3.2). However, due to the persistent lack of clear regulations at the state level, many uncertainties remain regarding the application of compensation mechanism.

The LR deforestable surplus is defined as areas of forest that are surplus to the legally required LR, and can therefore be legally deforested (forest cover over 80% of each property). This does not include areas of forest that are additional to the minimum cover stipulated by reduced compliance requirements in areas that have been historically deforested. For example, for medium and large properties in areas zoned for agricultural activities with more than 50% but less than 80% cover, the forest cover that is additional to 50% can be used to compensate for properties that are in deficit (termed compensation-only surplus), but cannot be deforested. The total area of forest available for compensation schemes is the sum of the deforestable surplus and the compensation-only surplus (termed here total surplus) (Table S3.2).

3.4. Results

Of the total required Legal Reserve area in Pará (21.2 Mha), 10.7% (2.3 Mha) was classified as a LR deficit; 6.4% (1.3 Mha) as deforestable surplus and 53.1% (11.3 Mha) as compensation-only surplus (Fig. 3.4, 3.5 and Table S3.4). The remaining area is covered by forest that cannot be deforested or used for compensation.

3.4.1. Distribution of Legal Reserve deficit in Pará

A total of 23 Mha of CAR and 12 Mha of rural settlements were analyzed in this study, accounting for 29% of the surface area of Pará and 61% of its registerable area. The estimated total forest deficit in Pará covers 2.3 Mha and is made up by properties in CAR and rural settlements (Fig. 3.4a). The LR deficit in CAR corresponds to an area of ~2 Mha (87% of the total deficit). The majority of this (50.4%) is within properties that have 0-30% deficit, while 48.2% is within properties that have 30-60% deficit and the remaining 1.4% for properties that have 60-80% deficit (Fig. 3.4a; Table 3.1). Settlements were found to contain a deficit of 300,389 ha - about 13% of the total LR area requirement for this type of land tenure. Virtually all the LR deficit found in settlements (99.3%) corresponds to properties that have a deficit of less than 30%.

Table 3.1. Legal Reserve (LR) deficit, deforestable surplus, compensation-only surplus, total surplus and Legal Reserve balance ([1]Surplus minus Deficit) in state of Pará by private property registered in the Environmental Rural Property Register (CAR) and rural settlements.

Categories	LR Classes	LR Defict (ha)	LR Defict (%)	LR Deforestable surplus (ha)	LR comp.-only surplus (ha)	LR total surplus (ha)
CAR	0-30%	992,828	50.4	699,924	2,271,060	2,970,984
	30-60%	948,556	48.2	-	878,407	878,407
	60-80%	27,326	1.4	-	747,169	747,169
	80-100%	-	-	-	173,446	173,446
	Total	1,968,710	100	699,924	4,070,082	4,770,006
Rural settlements	0-30%	298,297	99.3	656,762	375,984	375,984
	30-60%	1,047	0.3	-	1,266,943	1,266,943
	60-80%	1,046	0.3	-	3,801,909	1,227,423
	80-100%	-	-	-	1,756,305	4,980,451
	Total	300,390	100	656,762	7,201,141	7,850,802
Sum of totals		**2,269,100**	-	**1,356,686**	**11,271,223**	**12,620,808**
LR Balance[1]	-	**-**	-	**-912,414**	**9,002,123**	**10,351,708**

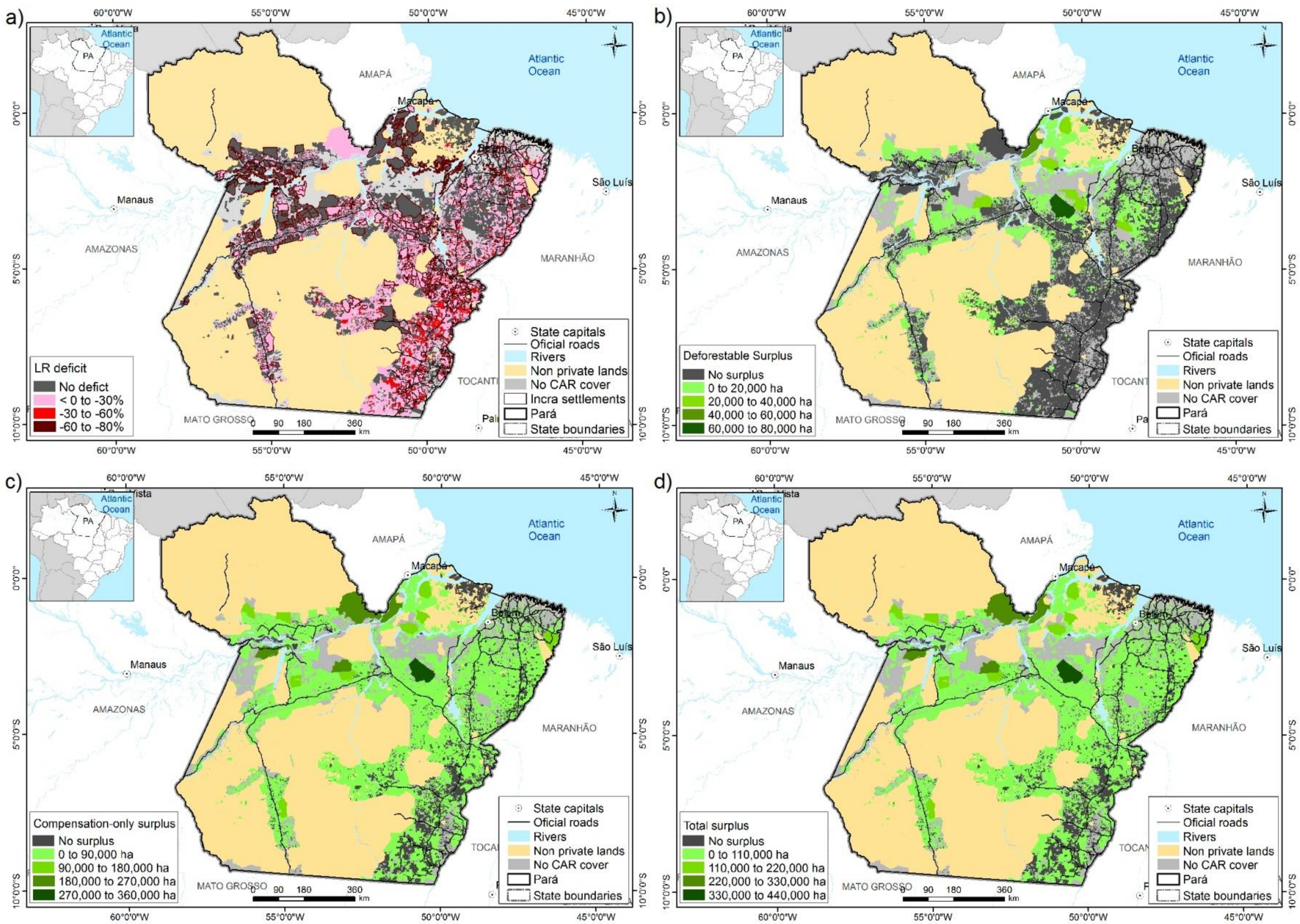
a)
LR deficit
No defict
< 0 to -30%
-30 to -60%
-60 to -80%
State capitals
Oficial roads
Rivers
Non private lands
No CAR cover
Incra settlements
Pará
State boundaries
b)
Deforestable Surplus
No surplus
0 to 20,000 ha
20,000 to 40,000 ha
40,000 to 60,000 ha
60,000 to 80,000 ha
c)
Compensation-only surplus
No surplus
0 to 90,000 ha
90,000 to 180,000 ha
180,000 to 270,000 ha
270,000 to 360,000 ha
d)
Total surplus
No surplus
0 to 110,000 ha
110,000 to 220,000 ha
220,000 to 330,000 ha
330,000 to 440,000 ha
Atlantic Ocean
AMAPÁ
Macapá
Belém
São Luís
Manaus
AMAZONAS
MARANHÃO
MATO GROSSO
60°0'0"W
55°0'0"W
50°0'0"W
45°0'0"W
0°0'0"
5°0'0"S
10°0'0"S
0 90 180 360 km

Figure 3.4. Distribution of Legal Reserve (as defined by the 2012 Brazilian Forest Code) in rural properties registered under CAR and settlements: a) deficit (forest cover under the required LR: negative values); b) deforestable surplus (forest cover over 80% of each property); c) compensation-only surplus (forest cover that can used for compensation purposes only but not deforested); d) total surplus (deforestable surplus and compensation-only surplus

3.4.2. Distribution of deforestable surplus and compensation-only surplus in Pará

The deforestable surplus in Pará represents an area of 1.3 Mha (Fig. 3.4b, Table 3.1). The Marajó region alone holds 36% of the deforestable LR surplus for the state (Table S3.5). The compensation-only surplus covers 11.2 Mha (Fig. 3.4c, Table 3.1). From the total area of compensation-only surplus, 8.7 Mha (1.5 million from CAR and 7.1 million from settlements) is relative to the current forest cover of small properties and 2.5 Mha from medium and large properties with 50% to 80% of forest cover. Thus, the total surplus estimated in this study, including deforestable surplus and compensation-only surplus, is 12.6 Mha (Fig. 3.4d, Table 3.1).

Accounting for both total surplus and total deficit the LR balance for the state gives a surplus of 10.3 Mha, due especially to the contribution of compensation-only surplus, which accounts for 17% of the private land area available for CAR registry in Pará (Fig. 3.4; Table 3.1). Conversely, taking into account only the deforestable surplus, the LR balance for Pará would give a deficit of 912,414 ha (Table 3.1).

3.4.3. Distribution of Legal Reserve deficit and total surplus across properties of different sizes

Rural settlements account for the highest percentage of compensation-only surplus (96.7% - 7.2 Mha), as a percentage of the required LR area for this category, followed by the three classes of small properties (Fig. 3.5a; Table S3.4). Settlements also presented the highest percentage of deforestable surplus (8.8% - 656,762 ha), followed by large and medium-sized properties. The LR deficit was mostly made up by medium (22.6% - 605,900 ha) and large (12.9% - 1.2 Mha) properties, followed by the three classes of small properties (Fig. 3.5a; Table S3.4) (Fig. 3.5b; Table S3.4).

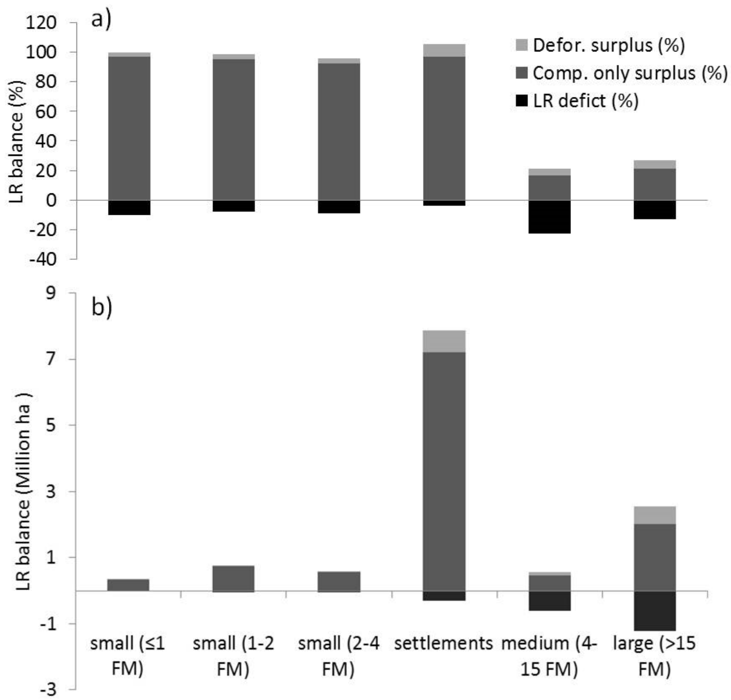

Figure 3.5. Legal Reserve balance by property size as (a) a percentage of the required LR and (b) total area in the in the state of Pará. Property size is defined in terms of the number of fiscal modules (FM).

3.4.4. Distribution of Legal Reserve deficit and total surplus across municipalities

The Legal Reserve of each of the 144 municipalities in the state of Pará was calculated as the total surplus (compensation-only surplus and deforestable surplus) minus the total deficit per municipality (Legal Reserve balance). We found that 32 municipalities (22% of the state total) presented more deficit than surplus (Fig. 3.6; Table S3.6) – amounting to a total of 382,521 ha, or 17% of the total deficit in private properties in Pará. In all cases the deficit of these 32 municipalities could be compensated for by the surplus provided by one or more neighboring municipalities, if the landowners do not restore forest on open land within the same municipality where the deficit occurred. The remaining 83%, or 1.8 Mha, of deficit that is distributed across 111 (77% of the total) municipalities can be compensated within the same municipality if landowners choose not to restore on their own properties. Only one municipality (Santa Cruz do Arari) was mapped as neutral (no LR deficit or surplus) (Fig. 3.6; Table S3.6).

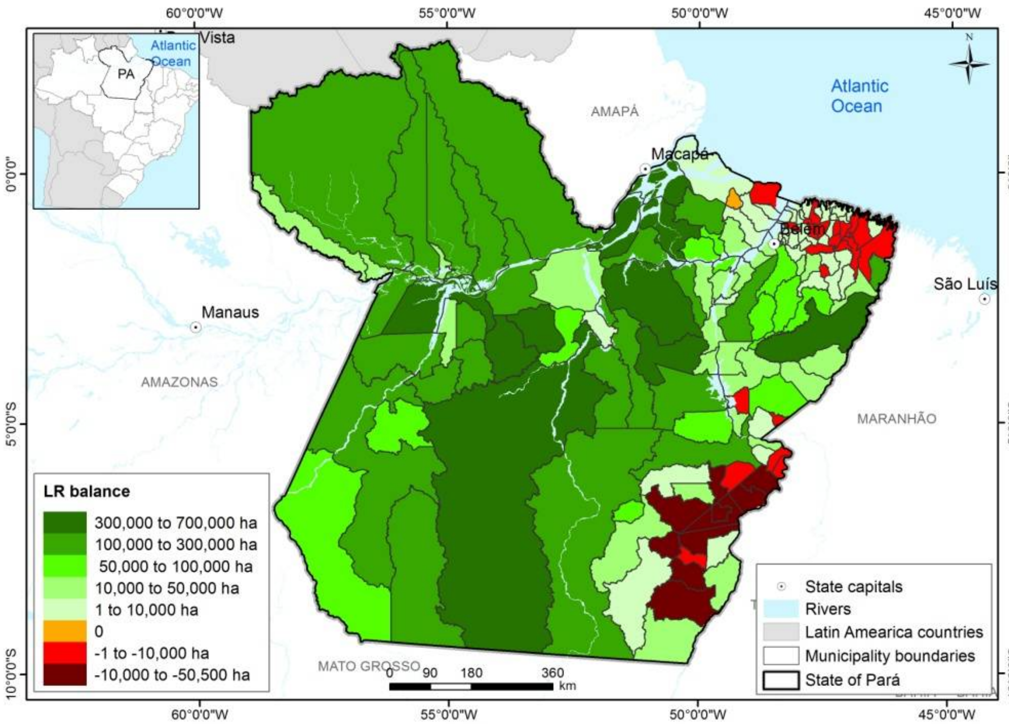

Figure 3.6. Legal Reserve balance (Surplus minus Deficit) by municipality, as a percentage of the adjusted LR requirement for each municipality, according to the updated Brazilian Forest Code. Positive values indicate Legal Reserve surplus is higher than the deficit area and negative values indicate Legal Reserve deficit is higher than the surplus area. Zero indicates neutral municipalities (no deficit or surplus).

3.5. Discussion

Our estimate of the total LR surplus for the 35 Mha of registered properties (CAR and agrarian reform settlements - 58,835 properties) we assessed in Pará was more than five times the total area of deficit. Medium and large properties contributed the most to the total deficit area (22.6% and 12.9%, respectively), while agrarian reform settlements had comparatively large amounts of both compensation-only surplus and deforestable surplus. Of the municipalities that have properties in deficit, 111 could compensate their deficit with surplus areas within the same municipality while the remaining 32 could compensate from surplus areas in one or more of the neighboring municipalities, indicating that, in theory, compensation can always take place close to the source of the deficit. It is important to highlight that the vast majority (90%) of LR surplus we mapped in Pará is compensation-only surplus that cannot be legally deforested. Furthermore, the opportunities given to the landowners to reduce a deficit are flexible and this makes it difficult to define or predict the alternative compliance pathways (i.e. blends of on-farm restoration and compensation from different regions) that are likely to be adopted and therefore their implications for the conservation of remaining forests.

3.5.1. Legal Reserve deficit and surplus across Pará

The distribution of LR deficit and surplus in Pará is clearly related to the historical land-use and occupation process in the region. The largest concentration of LR deficit in the State is located in its southeast region (Fig. 3.4a), mostly due to economic activities such as cattle ranching, practiced in the region since the 1970s when the Brazilian government encouraged immigration and deforestation to guarantee land tenure. Areas where the agricultural frontier is less advanced and with large conservation units (e.g. Calha-Norte, northwest of Pará), and/or low population density (like Marajó), in part due to the inaccessible nature of these regions, still retain large amounts of LR surplus (Fig. 3.4a).

The deficit and surplus found in agrarian settlements are associated with the nature of the settlements. For example, in Agro-Extractive Settlement Projects (PAE, in Portuguese) and Sustainable Development Settlements (PDS, in Portuguese), only low impact activities are allowed and represent the majority of the surplus area. In the Federal Settlements Project (PA, in Portuguese), agriculture and cattle ranching are the main activities (more associated with deforestation), and represent the majority of the deficit area (Fig. 3.4a).

The total LR surplus of Pará, when taking account of both deforestable and compnsation-only surplus, is more than five times the total area of deficit in the state. This suggests that the total surplus of Pará could compensate for its entire deficit (2.3 Mha) with 10.3 Mha still left over that can be traded with states within the same biome, for example, Mato Grosso, a neighboring state that has also experienced high historical rates of deforestation. This means that properties interested in trading LR surplus could, in theory, be located in areas that are ecologically very dissimilar or in different biogeographic regions. It is therefore important to understand the extent to which achieving legal compliance with the Forest Code through off-farm compensation is possible within the same or neighboring municipalities compared to more distant areas.

The fact that the LR surplus in Pará is made up almost entirely of forest areas that cannot be legally deforested has three important implications. The first is that the trading of these forests to compensate for illegal deforestation elsewhere brings no additional conservation benefit in and of itself. This is in contrast to the case of deforestable surplus that, if protected, could prevent primary forest from being cleared. The second is that these forests could provide a welcome income stream for farmers who have historically been more law abiding – including many smallholders. Finally, there is very little incentive for restoration activities, even in areas important for endemic biodiversity (i.e. species that are native or restricted to a certain area), or areas where the supply of ecosystem services is severely diminished. Given that when allowed by law (i.e. they have more than 80% forest cover) landowners still have more incentives to clear forest than rent deforestable land for compensation purposes, LR deficits are likely to be resolved through compensation-only surplus unless new incentives or conditions are created to encourage the protection of deforestable surplus through legal reserve trading.

3.5.2. Achieving legal compliance across actors and municipalities and maximising returns for conservation

The distribution of LR deficits and surpluses varies across properties of different sizes and between municipalities. Understanding this variability is key to assessing the potential for different actors to achieve legal compliance and hence the most appropriate mix of policy measures and incentives to ensure that regulations are enforced effectively and fairly (Godar *et al.*, 2014). The relative contribution of total surplus and compensation-only surplus was greater for small properties and settlements; and the contribution of deforestable surplus was higher for rural settlements, suggesting that some of the poorest landowners would be able to receive an important income stream from landowners in deficit. This high proportion of compensation-only surplus in small properties can be partly explained by the fact that all current vegetation in small properties can be used to compensate deficit, compared to medium and large properties where only the portion of forest cover that is between 50-80% of each property can be used for the same purpose. In addition, smallholder-dominated areas generally contain more forest than areas dominated by large landowners who are more likely to engage in extensive cattle ranching and large-scale agriculture, and forests in smallholder dominated areas are usually less fragmented and degraded (Godar *et al.*, 2014).

Under the updated Forest Code landowners have a range of options to reduce LR deficit, including: (i) the opportunity to compensate a deficit anywhere, as long as it is within the same biome where deficit occurred; (ii) use of both native vegetation and secondary forest in any stage of regeneration for compensation purposes; and (iii) restoration of forest on the farm which has the deficit instead of compensating in other places. These broad ranges of options have very different consequences for biodiversity conservation.

At the municipality scale, despite the 2.3 Mha of LR deficit found in Pará, 77% of the municipalities (111) can compensate all of their deficit – amounting to 83% of the total deficit of the state in private properties- within the same municipality. This provides an important opportunity for the government to guide (whether through regulation or incentives) compensation and restoration actions to remain within the same municipality in order to maintain locally important ecosystem services and strengthen the conservation of regionally endemic and often endangered biodiversity. Furthermore, promoting legal reserve trading between neighboring municipalities can reduce the transaction costs of matching supply and demand for ad hoc agreements – which are likely to dominate LR compensation mechanisms until a mature market system is in place. Nevertheless, 22% of the municipalities (32) have no choice but to compensate their LR deficit in other municipalities, owing to the lack of surplus locally. This deficit corresponds to 17% of the total deficit found in Pará, and in such cases it will be important to incentivize compensation within the same biogeographic regions.

Thus, efforts should be made to first ensure the protection of existing biodiversity and avoid further deforestation, and then to mitigate and compensate for impacts that have already occurred (McKenney and Kiesecker, 2010; Bull *et al.*, 2013). Maximising the environmental benefits of achieving Forest Code compliance requires measures and considerations that go beyond the existing legal framework. These include (i) conservation of deforestable surplus, even where forests are degraded. To improve the potential conservation dividends from the compensation-only surplus the government could use the compensation regulatory system as a mechanism to avoid further deforestation of standing forests, e.g. through clear incentives or conditions to prioritize compensation with the remaining deforestable surplus; (ii) promotion of local compensation wherever possible. The net effects of achieving legal compliance through offsets that are not like for like (e.g. compensating in areas where the species composition is different) will result in an overall loss of biodiversity, particularly as the regions with the highest deficit lie within some of the most threatened areas of endemism, such as Belém, which contains more threatened species than anywhere else in the Brazilian Amazon (Moura *et al.*, 2014); (iii) encourage avoidance of forest degradation and restoration actions in areas that are severely degraded. In addition to conservation actions to protect forest from being degraded, there could be advantages of encouraging local forest restoration in municipalities that would otherwise have to compensate remotely. This would help guarantee a reduction in forest fragmentation and an overall gain in ecological connectivity and habitat for forest species in the medium/long term.

3.5.3. Technical challenges and barriers to addressing the Legal Reserve deficit in Pará

A number of technical challenges must be addressed in order to obtain reliable assessments of environmental liabilities, facilitate law enforcement, monitoring and ensure that legal reserve deficits are fully and appropriately compensated. First, more accurate and representative georeferenced register of private properties (CAR) are required in the Amazon region. Despite the fact that the state of Pará is the most advanced Brazilian state in registering its private properties in the CAR system (Whately and Campanili, 2013), many municipalities present very low coverage of CAR, such as Quatipuru (3%) and Augusto Corrêa (5%) (SEMA/Imazon, 2016). Furthermore, the Secretary of State for the Environment estimates that only 4,000 of approximately 100,000 properties registered in CAR in the state have been validated on the ground (Ausier, 2013). Thus, the CAR database presents many uncertainties regarding overlapping property boundaries, and the definition of legal reserve areas, productive land and APPs. For this reason, our analysis of existing CAR data may present potential issues with representativeness across the State, especially in the western region that encompasses most municipalities with CAR cover <50%, and is therefore likely to be the least representative coverage. However, this region also has the highest portion of protected areas and lowest deforestation pressure due to accessibility. We therefore believe that, even if the whole registerable area was mapped, the pattern of distribution of deficit and surpluses would not change significantly across the State.

Second, the accuracy of Geographic Information Systems (GIS) and remote sensing products are limited by the quality (or lack) of mapping data, especially in the Amazon region (Silva *et al.*, 2013). Is this study we have not estimated deficit in APPs due to the lack of detailed (1:50.000) and reliable hydrological maps for Pará, which are required by law in Brazil (Decree N° 7.830, 17 October 2012 for the National CAR System). Moreover, official data on land use and land cover for the Amazon are not always accurate, despite being the best available source of information at large spatial scales. We have estimated an area of 1 Mha detected by TerraClass as deforestation in 2008 and as secondary forest in 2010. In a 2-year-window it is unlikely that regenerating forests can be classified as secondary forest, as defined by the TerraClass systems as forests at an advanced stage of regeneration (Embrapa and INPE, 2011), implying a potential overestimate of secondary forest data. The age of secondary forest is important for law enforcement, because different ages of forest require different licenses for cleaning or deforestation (i.e. forests older than five years can be protected from deforestation, depending on its structure) (Normative Instruction N° 08, 03 November 2015).

Finally, the complexity of Brazilian environmental laws have led to misunderstandings and controversies among different sectors (for example government, NGOs and farmers) on how to enforce the law and estimate legal liabilities (LR and APP deficits) (Ellinger and Barreto, 2012; Vale *et al.*, 2014). Such controversies have resulted in legal actions from the Federal Prosecutor's Office against several articles of the Forest Code (Federal Prosecutor's Office, 2014).

It is important to note that Forest Code states that if deforestation occurred during a time when the law required a lower level of LR, then the land owners are exempt to restore or compensate forest if they complied with the legislation in force at the time (Art. 68). However, due to the lack of any property database for the past decades, these cases were not considered in the analysis. To benefit from this clause, the land owner must prove to the state Environmental Secretary the existence and size of the property at the time it was governed by a lower LR requirement. Although this is impossible to assess based on information that is currently available, we do not believe this limitation would change the overall results of this paper, since this rule is mostly applicable to regions where 80% of LR is required, which is a fairly small area (~8% of the state).

For a more complete diagnosis of LR deficit in the State, as required by law, more detailed mapping and assessment of APPs is essential to estimate the potential for forest restoration in Pará. Considering that the LR deficit in Pará could be completely compensated by compensation-only surplus areas, and the little (or lack) of incentive to retire areas of productive land or restore forests in the LR, restoration activities can be expected to be more focused in APPs, where it is mandatory, compared to LRs where it is voluntary. However, it is currently not possible to evaluate to what extent forests will be compensated or restored to achieve compliance with the Forest Code.

3.6. CONCLUSIONS

While Brazil has one of the most complex and advanced set of environmental laws, our results are relevant to the governance of forests on private lands in many other tropical forests nations. Wherever environmental laws require landowners to maintain a certain amount of forest cover, there are regulations regarding forest deficit or surplus that must be understood, and the implications of this balance for forest management at both local and large scales needs therefore to be assessed. In this study, we show that there was a significant LR surplus that is five times the deficit estimated in the state, despite the historical development of agriculture frontier in Pará. That said the amount of forest available for compensation can only be considered a potential surplus because it is impossible say to what extent landowners will opt to compensate or restore to resolve the deficit of individual properties.

To maximize the conservation benefits of efforts to achieve compliance with the Forest Code additional measures are needed that are outside the existing legal framework. These include: the use of incentives or regulations to prioritize off-farm compensation in properties that still retain a deforestable surplus; encouraging off-farm compensation to happen as locally as possible to guarantee the protection of biodiversity in ecologically similar forests to those where the deficit occurs; and encouraging restoration of forests in areas where remnant forests are highly fragmented , as well as additional conservation actions to encourage avoidance of degradation in areas that are not under threat of deforestation but stand to be severely degraded from the impacts of logging and fire.

3.7. Acknowledgements

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3.9. SUPLEMENTARY INFORMATION

S3.9.1 Geographic database

In order to estimate the Legal Reserve deficit and surplus for each property registered in the Pará Rural Environmental Registry (CAR), according to the updated Brazilian Forest Code, we used a set of geographic database such as properties registered in CAR, land cover, vegetation typology, protected areas and agrarian reform settlements (Table S3.1). The geographic coordinated system used for all database was Lambert Conformal Conic, datum Sirgas 2000.

Table S3.1. Geographic database used in the study.

Geographic database	Source	Year
CAR (definitive and temporary)	SEMAS-Pará	Dec/2013
Deforestation	Prodes/Inpe	Up to 2008 Up to 2012
Forest	Prodes/Inpe	2008 2012
Regrowth	TerraClass/Inpe	2008 2010
Vegetation typology	IBGE	-
Protected areas	ISA	2013
Rural settlements	Incra	2013
Hydrography	IBGE	-
Roads	Imazon	2010

S3.9.2. Accounting for Legal Reserve deficit and surplus

In order to estimate LR deficit and different types of surplus by property size, we adopted in this study some concepts based on the Brazilian environmental law that guided the methodology to account for deficit and surplus (Table S3.2).

Table S3.2. Definition of Legal Reserve deficit, deforestable surplus, compensation-only surplus and total surplus across properties of different sizes (according to the number of fiscal modules – FM), adopted in this study and based on the updated Forest Code.

Property size	Deficit	Deforestable surplus	Compensation-only surplus	Total surplus
Small (≤4FM)	forest cover under the required LR	forest cover over 80% of the property	Existing forest cover under 80% of the property	Def. surplus + compensation-only surplus
Medium (4-15 FM); Large (>15 FM)	forest cover under the required LR	forest cover over 80% of the property	Forest cover 50-80% of the property	Def. surplus + compensation-only surplus

S3.9.3. Defining Legal Reserve according to the updated Brazilian Forest Code

The definition of the percentage of LR in rural properties is based on several conditions established in the updated Forest Code and specified in section 3.3.4 in main manuscript (see rules "a" to "d"). The number of properties and the proportion of the total sample of properties that were found to be eligible for each rule are presented in Table S3.3. A map of the 17 municipalities considered eligible for a reduction of LR of up to 50% of each property due to protected area coverage being >50% of each municipality (see 3.3.4a, main manuscript) is shown in Fig. S3.1.

Table S3.3. Number and proportion of properties eligible for each rule of Legal Reserve according to the Forest Code.

LR rules	Description	# of properties	% of properties
a	Reduction of up to 50%	9475	16,1
b	For small properties	44733	76,0
c	For vegetation other than forest	1394	2,4
d	Remaining areas (LR=80%)	3234	5,5
Total		**58836**	**100**

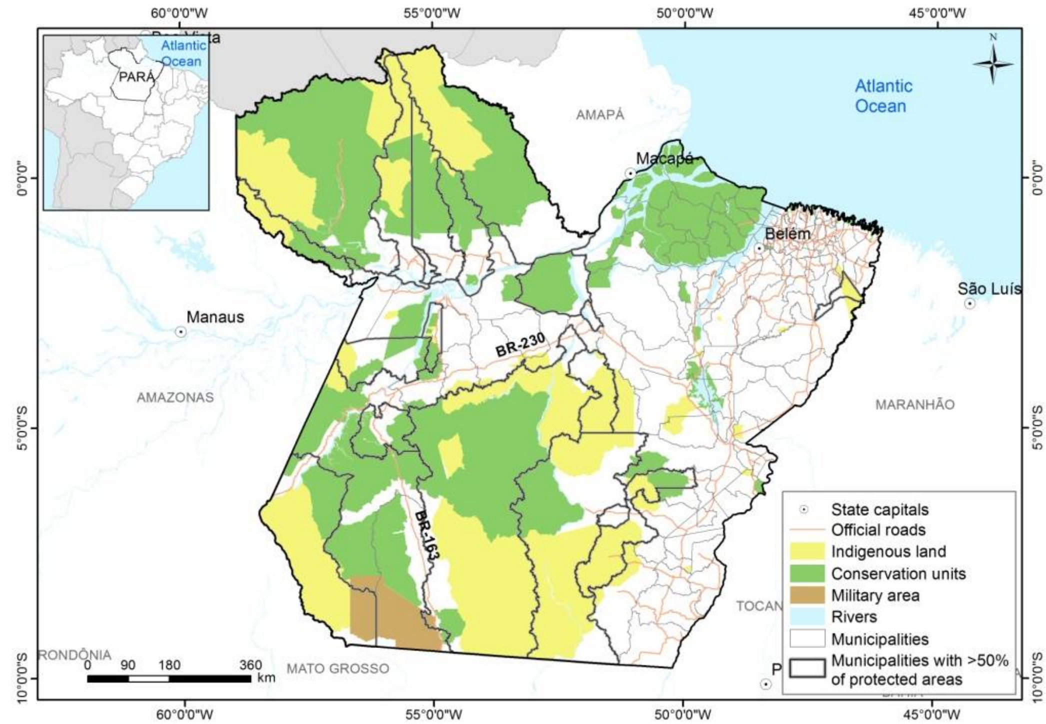


Figure S3. 1. Municipalities considered eligible for a reduction of LR of up to 50% of each property due to protected area coverage being >50% of each municipality.

S3.9.4. Results on the distribution of Legal Reserve deficit and total surplus across properties of different sizes

The LR deficit, compensation-only surplus, deforestable surplus and total surplus were evaluated for four different categories of properties (small, medium, large and rural settlements) under the updated Forest Code, as a percentage of the required LR for Pará (Fig. 3.5, in main manuscript; Table S3.4).

Table S3.4. Legal reserve deficit, compensation-only surplus, deforestable surplus and total surplus as a percentage of the required LR area for each property size (according to the number of fiscal modules – FM) in the State of Pará.

Property sizes	Required LR (ha)	LR defict (ha)	LR defict (%)	Comp. only surplus (ha)	Comp. only surplus (%)	Defor. surplus (ha)	Defor. surplus (%)	Total Surplus (ha)	Total Surplus (%)
small (≤1 FM)	332,075	33,852	10.2	320,619	96.6	10,095	3.0	330,714	99.6
small (1-2 FM)	771,018	60,573	7.9	733,685	95.2	24,267	3.1	757,951	98.3
small (2-4 FM)	607,531	52,923	8.7	559,872	92.2	21,410	3.5	581,281	95.7
Ruralsettlements	7,447,737	299,343	4.0	7,200,853	96.7	656,762	8.8	7,857,615	105.5
medium (4-15 FM)	2,676,695	605,900	22.6	448,563	16.8	115,325	4.3	563,888	21.1
large (>15 FM)	9,404,409	1,215,462	12.9	2,007,318	21.3	528,827	5.6	2,536,146	27.0
Total	21,239,464	2,268,053	10.7	11,270,910	53.1	1,356,686	6.4	12,627,595	59.5

S3.9.5. Results on the distribution of Legal Reserve deficit and total surplus across mesoregions

Legal Reserve deficit, compensation-only surplus and deforestable surplus were also evaluated for the six Pará mesoregions (Fig. 3.1, in main manuscript) as a percentage of the required LR area for each mesoregion. We found that Marajó and Baixo Amazonas presented the highest percentage of compensation-only surplus (77.8% and 74.3%, respectively) in Pará, followed by Belém (66%) and Sudoeste Paraense (65.9%). Marajó also presented the highest percentage of deforestable surplus (16.5%), followed by Sudoeste Paraense (7.4%) and Nordeste Paraense (6.9%). The LR deficit was mostly represented by Sudeste Paraense (20.2%) and Belém (12.9%), followed by Nordeste Paraense (8.8%) (Fig. S3.2a; Table S3.5). Baixo Amazonas is the most representative mesoregion in terms of compensation-only surplus absolute area (2,657,690 ha), followed by Sudoeste Paraense (2.596.219 ha). Marajó has the largest deforestable surplus area (482.538 ha), followed by Sudoeste Paraense (290.933 ha). Sudeste Paraense and Sudoeste Paraense presented the highest deficit area (1,665,730 and 243,087 ha, respectively) (Fig. S3.2b; Table S3.5).

For the most preserved mesoregions Baixo Amazonas, Sudoeste Paraense and Marajó – and also for the Nordeste Paraense due to the recent government actions to reduce deforestation and to promote forest restoration - the contribution of compensation-only surplus and deforestable surplus was higher when compared to the other mesoregions. Sudeste Paraense and Belém mesoregions, the most disturbed areas, presented the highest LR decifit in Pará.

Table S3.5. Legal reserve deficit, compensation-only surplus, deforestable surplus and total surplus as a percentage of the required LR area for each mesoregion in the State of Pará.

Mesoregions	Required LR (ha)	LR deficit (ha)	LR deficit (%)	Comp. only surplus (ha)	Comp. only surplus (%)	Defor. surplus (ha)	Defor. surplus (%)	Total Surplus (ha)	Total Surplus (%)
Baixo Amazonas	3,576,492	86,639	2.4	2.657.690	74.3	237,407	6.6	2,895,097	80.9
Marajó	2,932,467	44,129	1.5	2,282,339	77.8	482,538	16.5	2,764,877	94.3
Belém	71,189	9,188	12.9	46,965	66.0	4,480	6.3	51,446	72.3
Nordeste Paraense	2,484,648	219,281	8.8	1,131,462	45.5	171,966	6.9	1,303,428	52.5
Sudeste Paraense	8,235,045	1,665,730	20.2	2,556,234	31.0	169,362	2.1	2,725,596	33.1
Sudoeste Paraense	3,939,624	243,087	6.2	2,596,219	65.9	290,933	7.4	2,887,152	73.3
Total	21,239,464	2,268,053	10.7	11,270,910	53.1	1,356,686	6.4	12,627,596	59.5

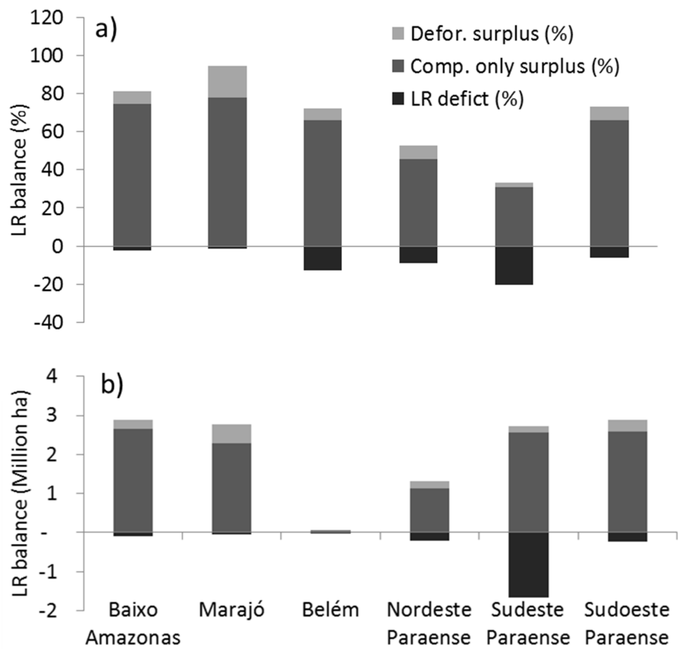


Figure S3.2. Legal reserve balance as (a) a percentage of the required LR and (b) total absolute area by mesoregions.

S3.9.6. Results on the distribution of Legal Reserve deficit and total surplus across municipalities

The LR deficit and surplus were evaluated by municipality in the State of Pará as a percentage of the required LR for each municicipality. Portel, Breves, Afuá, Medicilândia and Pacajá presented the highest LR balance (total surplus minus deficit). Água Azul do Norte, Xinguara, Curionópolis, Rio Maria and Sapucaia presented the lowest LR balance (Figure 3.6, in main manuscript; Table S3.6).

Table S3.6. Legal Reserve deficit, total surplus (compensation-only surplus + deforestable surplus) and balance ([1]Total surplus minus Deficit) by municipality, as a percentage of the LR required for each municipality, according to the updated Brazilian Forest Code. Positive values indicate LR surplus is higher than the deficit area and negative values indicate LR deficit is higher than the surplus area.

Municipalities	Required LR (ha)	LR deficit (ha)	LR deficit (%)	Total Surplus (ha)	Total Surplus (%)	LR balance[1] (ha)
PORTEL	824,770	6,021	0.7	720,290	87.3	714,268
BREVES	408,199	124	0.0	481,408	117.9	481,284
AFUÁ	407,032	66	0.0	465,103	114.3	465,037
MEDICILÂNDIA	424,820	4,456	1.0	454,295	106.9	449,839
PACAJÁ	634,123	43,395	6.8	465,667	73.4	422,272
URUARÁ	426,724	8,961	2.1	425,581	99.7	416,620
SANTARÉM	376,174	815	0.2	371,061	98.6	370,245
PARAGOMINAS	1,084,213	60,559	5.6	418,796	38.6	358,237
GURUPÁ	341,457	24	0.0	351,071	102.8	351,047
ALTAMIRA	743,918	73,416	9.9	402,472	54.1	329,056
SÃO FÉLIX DO XINGU	1,798,538	288,631	16.0	588,138	32.7	299,507
PLACAS	287,578	5,368	1.9	297,274	103.4	291,906
ORIXIMINÁ	313,796	1,735	0.6	293,555	93.5	291,819
MOJUÍ DOS CAMPOS	270,847	5,192	1.9	271,797	100.4	266,605
ALMEIRIM	839,523	43,446	5.2	300,205	35.8	256,759
ITAITUBA	373,173	17,632	4.7	258,118	69.2	240,486
RURÓPOLIS	225,995	4,352	1.9	244,207	108.1	239,854
ALENQUER	295,884	6,623	2.2	242,271	81.9	235,648
NOVO REPARTIMENTO	489,232	80,377	16.4	298,539	61.0	218,162
SENADOR JOSÉ PORFÍRIO	264,116	6,106	2.3	220,736	83.6	214,630
NOVO PROGRESSO	413,253	26,390	6.4	232,875	56.4	206,486
MELGAÇO	177,224	458	0.3	205,109	115.7	204,651
PRAINHA	217,593	6,954	3.2	184,314	84.7	177,360
ÓBIDOS	207,256	2,520	1.2	176,691	85.3	174,171
MONTE ALEGRE	188,251	6,105	3.2	178,253	94.7	172,147
AVEIRO	182,723	1,411	0.8	173,422	94.9	172,011
ANAJÁS	186,843	18	0.0	169,132	90.5	169,114
ANAPU	309,433	31,624	10.2	191,437	61.9	159,813
MOJU	347,287	18,376	5.3	166,126	47.8	147,751
CACHOEIRA DO PIRIÁ	180,243	21,149	11.7	157,686	87.5	136,537
JURUTI	137,285	15	0.0	128,355	93.5	128,340
MARABÁ	497,187	101,094	20.3	216,440	43.5	115,346
BAGRE	149,966	33	0.0	102,677	68.5	102,644
IPIXUNA DO PARÁ	243,710	9,946	4.1	108,652	44.6	98,706
TRAIRÃO	112,530	3,154	2.8	100,076	88.9	96,923
BRASIL NOVO	198,277	20,789	10.5	113,411	57.2	92,622
TAILÂNDIA	256,043	11,533	4.5	103,050	40.2	91,517
ITUPIRANGA	228,041	45,669	20.0	123,746	54.3	78,077
TUCUMÃ	71,420	0	0.0	72,253	101.2	72,253

TOMÉ-AÇU	204,008	11,937	5.9	83,088	40.7	71,151
JACAREACANGA	61,108	66	0.1	63,627	104.1	63,560
SÃO SEBASTIÃO DA BOA VISTA	54,053	0	0.0	62,938	116.4	62,938
LIMOEIRO DO AJURU	50,613	0	0.0	60,557	119.6	60,557
CURRALINHO	47,671	8	0.0	52,545	110.2	52,537
RONDON DO PARÁ	271,023	37,753	13.9	90,248	33.3	52,495
ACARÁ	99,697	3,468	3.5	53,501	53.7	50,033
ABAETETUBA	46,964	1,185	2.5	42,913	91.4	41,728
PORTO DE MOZ	52,943	1,781	3.4	43,304	81.8	41,523
BREU BRANCO	116,319	13,537	11.6	54,281	46.7	40,744
CURUÁ	43,361	643	1.5	40,013	92.3	39,370
OURILÂNDIA DO NORTE	69,753	7,342	10.5	45,824	65.7	38,482
BELTERRA	46,062	1,159	2.5	39,439	85.6	38,280
NOVA ESPERANÃA DO PIRIÁ	72,824	7,921	10.9	44,461	61.1	36,539
IGARAPÉ-MIRI	33,916	205	0.6	32,811	96.7	32,606
OEIRAS DO PARÁ	56,908	516	0.9	32,551	57.2	32,034
DOM ELISEU	258,731	46,076	17.8	75,180	29.1	29,103
MUANÁ	60,399	10,302	17.1	38,986	64.5	28,684
CAMETÁ	25,758	37	0.1	28,536	110.8	28,499
TUCURUÍ	88,683	8,418	9.5	36,155	40.8	27,737
CONCEIÇÃO DO ARAGUAIA	103,498	19,729	19.1	47,405	45.8	27,676
TERRA SANTA	31,058	508	1.6	26,986	86.9	26,478
FARO	26,167	486	1.9	25,474	97.3	24,987
BAIÃO	51,076	4,468	8.7	28,295	55.4	23,827
BARCARENA	20,455	10	0.0	22,827	111.6	22,817
GOIANÉSIA DO PARÁ	150,258	34,114	22.7	56,912	37.9	22,798
SÃO DOMINGOS DO CAPIM	29,762	7,393	24.8	30,046	101.0	22,653
ULIANÓPOLIS	258,940	43,861	16.9	66,411	25.6	22,549
NOVA IPIXUNA	40,489	7,406	18.3	26,742	66.0	19,336
SANTANA DO ARAGUAIA	459,856	104,641	22.8	122,398	26.6	17,756
CANAÃ DOS CARAJÁS	40,965	9,300	22.7	25,384	62.0	16,084
SÃO JOÃO DO ARAGUAIA	35,275	6,757	19.2	21,735	61.6	14,978
CONCÓRDIA DO PARÁ	16,257	2,482	15.3	14,208	87.4	11,726
CAPITÃO POÃO	54,899	11,073	20.2	19,423	35.4	8,351
MOCAJUBA	8,406	77	0.9	8,366	99.5	8,289
AURORA DO PARÁ	46,450	9,541	20.5	17,206	37.0	7,666
PARAUAPEBAS	21,538	4,586	21.3	10,976	51.0	6,390
BELÉM	5,227	0	0.0	6,150	117.7	6,150
PONTA DE PEDRAS	19,051	417	2.2	5,854	30.7	5,437
ANANINDEUA	4,177	0	0.0	4,919	117.8	4,919
BOM JESUS DO TOCANTINS	68,383	17,898	26.2	22,779	33.3	4,881
BUJARU	7,907	1,267	16.0	5,994	75.8	4,726
SÃO DOMINGOS DO ARAGUAIA	40,051	14,617	36.5	18,646	46.6	4,029
IRITUIA	20,347	6,910	34.0	10,809	53.1	3,899
VITÓRIA DO XINGU	65,100	20,337	31.2	24,188	37.2	3,850
CACHOEIRA DO ARARI	35,061	2,114	6.0	5,773	16.5	3,659

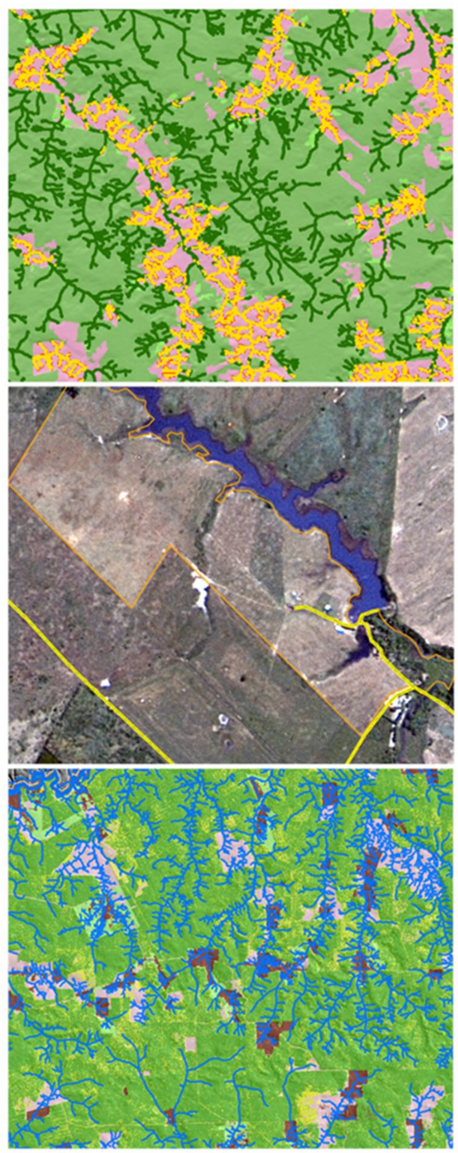
FLORESTA DO ARAGUAIA	45,318	13,672	30.2	16,715	36.9	3,044
GARRAFÃO DO NORTE	33,647	8,042	23.9	10,089	30.0	2,048
SANTA BÁRBARA DO PARÁ	3,320	217	6.5	1,524	45.9	1,307
CURUÇÁ	1,643	24	1.4	1,209	73.6	1,185
MARACANÃ	2,436	203	8.3	1,329	54.5	1,126
SALVATERRA	9,583	9	0.1	1,109	11.6	1,101
SANTA ISABEL DO PARÁ	8,784	2,033	23.1	3,095	35.2	1,062
SANTA MARIA DO PARÁ	2,410	660	27.4	1,600	66.4	941
CHAVES	124,658	12,556	10.1	13,483	10.8	928
CUMARU DO NORTE	634,781	104,955	16.5	105,841	16.7	886
INHANGAPI	7,845	1,323	16.9	2,118	27.0	795
CASTANHAL	13,635	4,021	29.5	4,775	35.0	754
COLARES	396	0	0.0	383	96.9	383
SÃO CAETANO DE ODIVELAS	2,476	519	21.0	894	36.1	375
PRIMAVERA	2,620	361	13.8	721	27.5	360
VIGIA	2,595	650	25.0	981	37.8	332
MAGALHÃES BARATA	829	95	11.5	427	51.4	332
QUATIPURU	349	0	0.0	241	69.0	241
AUGUSTO CORRÊA	665	0	0.1	144	21.6	143
SÃO JOÃO DA PONTA	547	102	18.7	222	40.6	120
SÃO JOÃO DE PIRABAS	2,485	420	16.9	510	20.5	90
SANTARÉM NOVO	1,311	336	25.6	422	32.2	86
BENEVIDES	993	158	15.9	232	23.3	74
MARITUBA	171	0	0.0	44	25.6	44
SALINÓPOLIS	27	0	0.0	27	100.0	27
NOVA TIMBOTEUA	7,632	1,830	24.0	1,851	24.3	21
SANTA CRUZ DO ARARI	6,265	0	0.0	0	0.0	0
JACUNDÁ	42,750	10,878	25.4	10,842	25.4	-36
SANTO ANTÈNIO DO TAUÁ	4,579	1,583	34.6	1,435	31.3	-148
ABEL FIGUEIREDO	10,525	3,574	34.0	3,115	29.6	-459
SÃO FRANCISCO DO PARÁ	7,692	3,590	46.7	3,113	40.5	-477
PEIXE-BOI	5,406	1,250	23.1	712	13.2	-538
MARAPANIM	3,648	1,656	45.4	955	26.2	-701
SÃO MIGUEL DO GUAMÁ	15,240	5,047	33.1	4,292	28.2	-755
SOURE	39,780	1,149	2.9	224	0.6	-925
TERRA ALTA	1,974	1,211	61.4	192	9.7	-1,019
CAPANEMA	4,583	2,063	45.0	681	14.9	-1,382
TRACUATEUA	4,370	2,146	49.1	673	15.4	-1,473
PALESTINA DO PARÁ	28,612	8,775	30.7	7,214	25.2	-1,561
PAU D'ARCO	54,557	9,122	16.7	6,947	12.7	-2,175
BRAGANÃA	9,434	3,424	36.3	1,156	12.3	-2,267
OURÉM	11,540	4,639	40.2	2,134	18.5	-2,505
BONITO	9,640	3,875	40.2	1,006	10.4	-2,869
ELDORADO DOS CARAJÁS	87,734	38,544	43.9	34,627	39.5	-3,917
IGARAPÉ-AÇU	11,940	6,709	56.2	1,764	14.8	-4,945
MÃE DO RIO	10,705	7,081	66.1	972	9.1	-6,109

VISEU	66,256	16,219	24.5	9,090	13.7	-7,129
BREJO GRANDE DO ARAGUAIA	33,893	15,298	45.1	6,492	19.2	-8,806
SANTA LUZIA DO PARÁ	18,569	10,926	58.8	1,812	9.8	-9,114
SANTA MARIA DAS BARREIRAS	315,582	81,066	25.7	68,244	21.6	-12,822
SÃO GERALDO DO ARAGUAIA	59,711	30,734	51.5	15,567	26.1	-15,166
BANNACH	112,820	39,379	34.9	23,109	20.5	-16,270
PIÇARRA	85,907	41,563	48.4	13,348	15.5	-28,214
REDENÃÃO	113,106	39,701	35.1	11,182	9.9	-28,519
SAPUCAIA	60,802	35,009	57.6	449	0.7	-34,560
RIO MARIA	152,881	62,876	41.1	20,431	13.4	-42,445
CURIONÓPOLIS	99,659	52,100	52.3	6,292	6.3	-45,808
XINGUARA	126,162	58,268	46.2	9,428	7.5	-48,840
ÁGUA AZUL DO NORTE	155,862	69,529	44.6	18,961	12.2	-50,568

Chapter 4

4. Assessing the conservation status of riparian forests in the eastern Brazilian Amazon

Publication status: To be submitted to Forest Ecology and Management



Assessing the conservation status of riparian forests in the eastern Brazilian Amazon

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4.1. ABSTRACT

The protection of riparian forests is of particular conservation importance as they help maintain the provision of key ecosystem services, such as the maintenance of water flows and the conservation of biodiversity and ecological connectivity. Nevertheless, riparian forests are particularly threatened across the tropics. Despite the significance of the Forest Code as the basis of environmental protection on private properties in Brazil, the effectiveness of the legal protection afforded to riparian vegetation in APPs has been very poorly assessed, particularly in the Brazilian Amazon. We provided the first analysis of the total riparian permanent preservation area distribution and deficit for the 1.25 Mkm^2 Brazilian state of Pará, which has the highest deforestation rate in the Amazon. Finally, Chapter 4 finds that, despite riparian APPs being mostly covered by forest in the state of Pará (63%), the area required to be restored by law (1 Mha) accounts for only about one-third of the deforested area that does not need to be restored following the 2012 revision of the Forest Code. This suggests that some important catchments in Pará may not recover fully functioning hydrological and ecological services, as around 2.7 Mha of consolidated APP are likely to remain deforested. We also demonstrated how coarse-scale mapping data consistently underestimates the extent of different APP areas, and thus the scale of the challenge presented by the compliance requirements of the forest code. The shortfall in riparian restoration must be met through incentives (e.g. provision of technical support on how to implement restoration, and education programs outlining the direct and indirect benefits from restoration of riparian vegetation) rather than regulations. Finer resolution land cover data and improved hydrological models are vital for ensuring the accurate implementation of Brazilian legislation and efforts to safeguard the environmental benefits provided by these critically important ecosystems.

Keywords: Brazilian environmental law, forest restoration, fine-scale imagery, coarse-scale imagery, permanent preservation areas, riparian forest.

4.2. Introduction

The protection of riparian forests is of particular conservation importance as they help maintain the provision of key ecosystem services, such as the prevention of soil erosion in agricultural systems, the maintenance of water flows and water quality, and the conservation of biodiversity and ecological connectivity (Rodrigues and Gandolfi, 2000; Lees and Peres, 2008; Castello *et al.*, 2013). Nevertheless, tropical riparian habitats (a combination of physical characteristics and water properties) have been changed by recent deforestation, agricultural mechanization and river fragmentation (Leal *et al.*, 2016). Riparian forests are particularly threatened across the tropics, especially where pasture is the most extensive form of land use (Kauffman and Krueger, 1984; Jansen and Alistar I., 2001). For example, riparian zones are commonly cleared to provide access for animals to water courses. Cattle are attracted by riparian zone due to the availability of water, shade, thermal cover and the quality of forage (Kauffman and Krueger, 1984; Jansen and Alistar I., 2001). Even when forests remain, they can be heavily degraded from trampling, grazing, erosion and edge effects, causing impacts on stream ecology, water quality and loss of fauna biodiversity (Kauffman and Krueger, 1984; Lees and Peres, 2008). Besides, the historical land use has caused impacts on stream hydrobiogeochemistry that extend beyond the adjacent forest. For example, the conversion of forest into pasture is changing water temperature, nutrient concentration and altered flow regimes (Figueiredo *et al.*, 2010; Neill *et al.*, 2011; Leal *et al.*, 2016).

To curb deforestation, the Brazilian government has invested significant effort in creating public protected areas (Chape *et al.*, 2005; Schmitt *et al.*, 2009; Veríssimo *et al.*, 2011). By 2012 approximately 46% of the Brazilian Amazon was under some form of public protection (ISA - Socio-Environmental Institute, 2012). However, public protected areas alone are unlikely to be adequate in ensuring either the protection of biodiversity or the maintenance of critical ecosystem services. For example, public protected areas often fail to effectively conserved hydrological catchments as headwaters are often located outside protected area boundaries (Silva Dias *et al.*, 2002; Soares-Filho *et al.*, 2006).

In contrast to many countries, riparian forests in Brazil are formally protected by a comprehensive set of regulations enshrined in the landmark federal Forest Code (Law N° 12,651, 2012). The Brazilian Forest code is widely lauded by policy makers and conservation organizations across the tropics as a model system that could be applied to strengthen conservation measures in other countries. As such, understanding the extent to which this legislation has been effective in delivering on-the-ground improvements in the conservation status of sensitive habitats like riparian forests is key to understanding not only its utility in Brazil but also its broader relevance to conservation strategies globally.

The Forest Code legislation defines riparian forests as a type of “permanent preservation area” (APP, in Portuguese) that were created to protect particularly environmentally sensitive areas in both private and public lands such as riparian vegetation, springs, steep slopes (>45°), hilltops and mangroves. The management activities permitted in APPs are strictly limited with only low impact activities allowed (e.g. ecotourism), with some amnesty in the updated Forest Code of 2012 allowing agrosilvopastoral systems in portion of APP areas deforested before July 2008 - hereafter termed ‘consolidated APP’. With the exception of consolidated APPs, deforestation of APPs is strictly prohibited and cleared areas must be restored either via direct plantings or natural regeneration (Brazilian Federal Government, 2012b). The shortfall of APP forest cover that is required to comply with the Forest Code is termed the APP deficit.

However, despite the significance of the Forest Code as the basis of environmental protection on private properties in Brazil, the effectiveness of the legal protection afforded to riparian vegetation in APPs has been very poorly assessed, particularly in the Brazilian Amazon. There are at least two main reasons for this. First, geographic information systems (GIS) and remote sensing products are essential for effective law enforcement (Firestone and Souza, 2002). However, the accuracy of maps of riparian forests and APPs more generally in the Amazon region is limited by lack of sufficiently fine-scale land cover and hydrography maps to estimate drainage networks and the width of water courses (1:50.000 at least - (Brazilian Federal Government, 2012a))

(Firestone and Souza, 2002; Zeilhofer *et al.*, 2011). For example, a small property must restore at least 5m of forest cover on each side of a river, which is impossible to assess using only a 30-meter resolution satellite, the finest-resolution imagery commonly available for the region. Indeed, land cover maps available for the Amazon are limited to 30-meter resolution, providing 1:100.000 scale maps (Zeilhofer *et al.*, 2011; INPE/TerraClass, 2012; INPE/PRODES, 2015). New work has started to develop maps at much finer resolutions but this has so far been limited to a small number of regions. For example, at the municipal level, only 30 out of 144 municipalities in the state of Pará have the land cover and rivers maps available at 1:25.000 scale using RapidEye imagery (Imazon and TNC, 2010). The mismatch in scale between available land cover maps and the size of the protection area buffers required by law leads to systematic errors in the setting of management plans and monitoring deforestation and forest cover in riparian zones (Zeilhofer *et al.*, 2011). In highly fragmented regions for example, small forest areas and small areas of deforestation can both be missed, severely undermining the integrity of the assessments.

Second, assessing the extent of legal liabilities (such as the deficit of riparian APP in a given private property compared to what is required by law) depends critically upon access to an accurate georeferenced register of private properties. The Environmental Rural Property Register (CAR, in Portuguese) is the major reference of rural properties in Brazil. However, many regions are still poorly covered by CAR such as in the South and Northeast of the country (33% and 37%, respectively), whilst areas that have much greater coverage (with the Amazonian states of Pará and Mato Grosso being the most advanced; MMA, 2016) still contain substantial errors (Nunes et al. 2016).

Here we provide the first analysis of the total riparian APP distribution and deficit for the state of Pará, which covers around 25% of the Brazilian Amazon at a 1:100.000 scale. In addition we assess 15 municipalities at a much finer-scale of 1:25.000. We use these data to address two specific questions: (i) What is the current status of riparian APPs across the state, including their total extent, forested extent and total area that is required to be restored by law? (ii) What uncertainty and potential bias is introduced into assessments of riparian forest when using coarse or fine-resolution land-cover and hydrological data?

4.3. MATERIALS AND METHODS

Within the state of Pará we assessed riparian APPs registered within the CAR system (36 Mha of CAR cover or 62% of the area suitable for CAR registry), and in unregistered areas to separately quantify the total APP area, deficit, APP with forest, and consolidated APP for all 144 municipalities in Pará. These analytical steps are summarized in Fig. 4.1 and described in detail below.

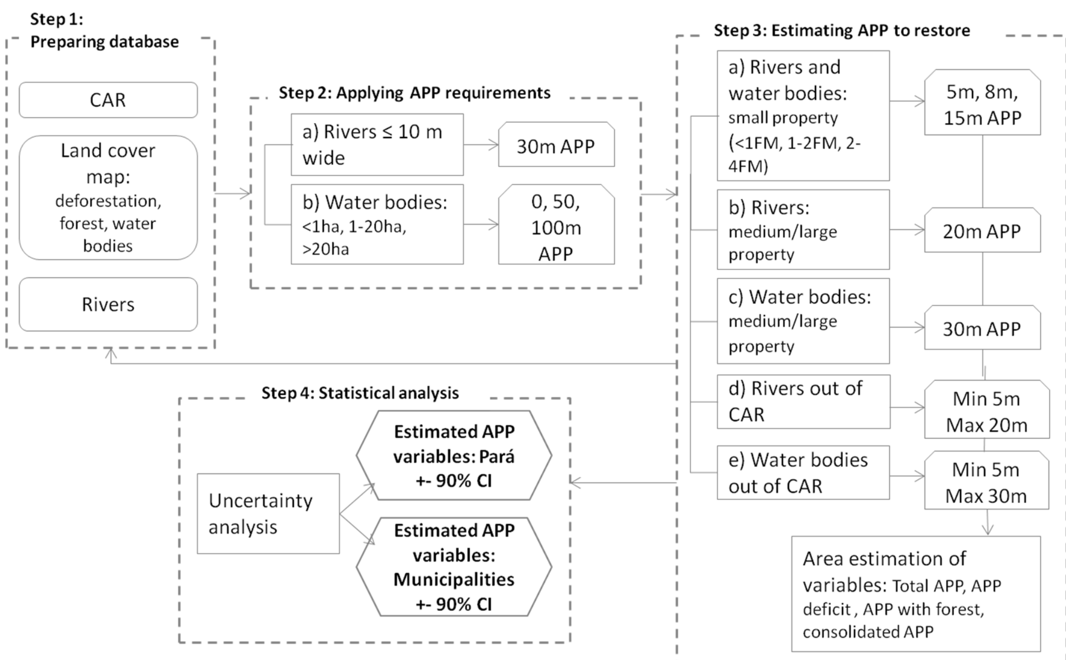

Figure 4.1. Summary of the methodology applied to evaluate permanent preservation areas (APPs) in the state of Pará. CAR stands for Environmental Rural Property Register, FM for Fiscal Modules and CI for Confidence Interval.

4.3.1. Study area

Our analysis is focused on the state of Pará, located in the eastern Brazilian Amazon (Fig. 4.2), because: (i) it is the most advanced state in the Amazon in registering its private rural properties in the CAR system; > 60% of the area suitable for registry was included in the state government database by 2015; (ii) it currently has one of the highest rates of deforestation in the Amazon: an average of 2,000 km^2/year from 2011 to 2015, compared to 5,500 km^2/year for the whole Brazilian Amazon, and (iii) state and municipal governments of Pará, together with civil society, have been particularly active in their efforts, to reduce deforestation and the state has been recognized as setting an example for other parts of the Amazon, eg. through Para´s Green County initiative.

With an area of 1.25 million km^2, Pará is the second largest state in Brazil, larger than many countries (e.g. Peru, South Africa), encompassing 144 municipalities and intersects five of the key areas of endemism in the Amazon. Its economy is mostly made up by extractive industry (e.g. iron, bauxite, wood, charcoal), agriculture (e.g. palm oil and cassava) and cattle ranching (Pará has the fifth largest cattle herd in Brazil – with 17 million heads in the 2013 census) (IBGE - Brazilian Institute of Geography and Statistics, 2013). Pará has about 55% of its territory, or 685,575 km^2, protected by law in sustainable-use, strictly protected, or indigenous reserves (Brazilian Ministry of the Environment and National Indian Foundation, 2013). However, it also had one of the highest rates of deforestation in the Amazon, which is related to the pattern of recent occupation and agricultural expansion.

In order to reduce deforestation rates and increase the property area registered under the CAR system, the government launched new strategies such as the Green Municipalities Program in partnership with municipalities, civil society, private initiatives and the Public Prosecution Service (Whately and Campanili, 2013). Despite considerable success in reducing deforestation, many challenges remain to reduce the c. 5000km^2 that are still cleared every year and to achieve compliance with the revised Forest Code. Land tenure remains a major issue across Pará: 39% of the state - mainly the eastern portion - has tenure irregularities. The remaining 61% that has defined tenure includes protected areas, agrarian reform settlements and registered properties.

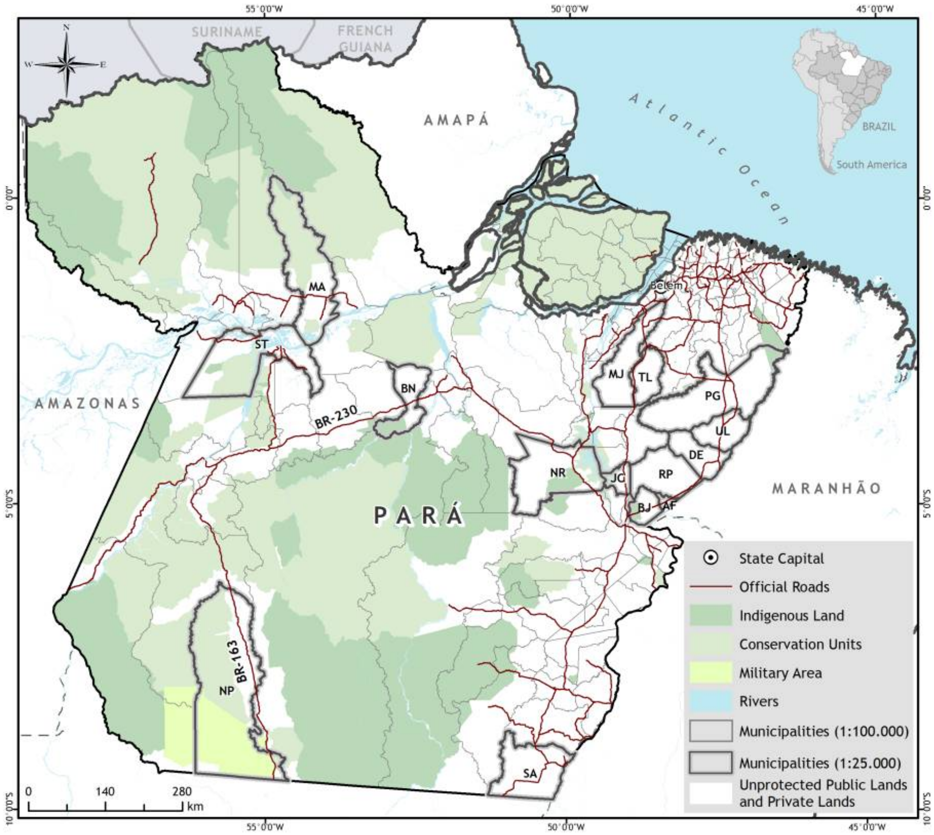

Figure 4.2. Study area, state of Pará, located in the Brazilian Amazon, northern Brazil. The fine-scale analysis was carried out for 15 municpailites of: Abel Figueiredo (AF), Bom Jesus do Tocantins (BJ), Brasil Novo (BN), Dom Eliseu (DE), Jacundá (JC), Moju (MJ), Monte Alegre (MA), Novo Progresso (NP), Novo Repartimento (NR), Paragominas (PG), Rondon do Pará (RP), Santana do Araguaia (SA), Santarém (ST), Tailândia (TL) and Ulianópolis (UL).

4.3.2. Geographic database

In order to estimate the Forest Code APP deficit for Pará we used a geographic database divided in two main scales: (i) 1:100.000, the official deforestation data from INPE, mapped by Prodes (Federal government deforestation monitoring program for the Amazon) and land-use classes mapped by TerraClass (Federal government land-use monitoring project for the Amazon) (Table 4.1; see supplementary information, section 4.8.1, for more details). Both used the 30-meter resolution Landsat images as a reference to map the land cover and land use, including deforestation, forest and water bodies (e.g. lakes, dams and large rivers) classes. This database was used for all 144 municipalities in Pará (Fig. 4.2); (ii) 1:25.000, land cover map developed by Imazon that uses 5-meter resolution Rapideye images to map the same land-cover classes and water courses. This database was used only for 15 municipalities (Fig. 4.2).

Table 4.1. Geographic database used in the study.

Geographic database	Source	Year	Scale	Image of reference
CAR	SEMAS-Pará	Mar/2015	-	-
Deforestation	Prodes/Inpe	2008-2014	1:100.000	Landsat
	TerraClass/Inpe	2012	1:100.000	Landsat
	Imazon	2009/2010	1:25.000	Rapideye
Forest	TerraClass/Inpe	2012	1:100.000	Landsat
	Imazon	2009/2010	1:25.000	Rapideye
Water bodies	TerraClass/Inpe	2012	1:100.000	Landsat
	Imazon	2009/2010	1:25.000	Rapideye
Rivers	SIVAM	2006	1:100.000	Landsat/SRTM
Rivers	Imazon	2009/2010	1:25.000	Rapideye/SRTM

4.3.3. Mapping of Permanent Preservation Areas

In order to map APPs it is necessary to first map the water courses. For this study, we considered only riparian APPs from rivers and APPs around water bodies (lakes and dams), which accounts for the majority of APP's in Pará, excluding the other types of APPs (e.g. headwaters, mangrove, sand dune vegetation, high declivity areas - > 45°). For the 15 municipalities mapped at 1:25.000, we used a semi-automated approach by combining SRTM with Rapideye images and a visual analysis to correct possible mistakes, such as underestimation of rivers (see supplementary information, section 4.8.2, for more details) (Souza Jr. *et al.*, 2013). The water courses mapped at 1:100.000 scale were obtained from INPE (Terra Class – water bodies) and SIVAM (rivers) for the 144 municipalities. At this scale it was possible to map up to three orders of rivers, compared to four from 1:25.000.

The second step was to map the APPs around the rivers and water bodies, according to Brazilian environmental law (Table 4.2, Fig. 4.3). The limitations for applying the APP width are listed below. Due to method limitations, some rules had to be adapted.

(i) All rivers mapped as line features were considered to be up to 10-meter wide, as the scale does not allow the mapping of variable width along small rivers. Thus, the APP width applied for those rivers was 30m;

(ii) All water courses wide enough to be mapped as polygons, or double line features, (including large rivers, lakes and dams), were classified as water bodies, since it was not possible to distinguish automatically the type of the water course. Given the two different scales used in this study, watercourses >15-meter wide were mapped as water bodies at the 1:25.000 scale for the 15 municipalities. For the 144 municipalities mapped at the 1:100.000 scale, only watercourses wider than 70-80m were mapped as water bodies.

Table 4.2. Buffers radius around rivers and water bodies used to map total permanent preservation areas (APPs) in Pará, based on the Brazilian Forest Code (Law N° 12,651, from 25th March 2012).

Water courses	Water courses width	APP width
Rivers	≤ 10 m wide	30m
Water bodies	< 1 ha	-
	1-20 ha	50 m
	> 20 ha	100 m

4.3.4. Mapping forest deficit in Permanent Preservation Areas

According to the Brazilian Forest Code the APPs width to be restored depends on the private property size, water course type and width and when the deforestation took place (Table 4.3, Fig. 4.3). Areas deforested up to 22nd July 2008 are termed 'consolidated rural areas'. In a specific portion of consolidated APPs that do not need to be restored, subsistence activities such as agrosilvopastoral system are allowed. In the remaining APP covered by forest, only low impact activities (e.g. ecoturism) are permitted. APPs deforested after this date must be entirely restored, regardless the size of the property or river width (Fig. 4.3).

Determination of the size of rural properties in Brazil is commonly based on the number of Fiscal Modules (FM), which is a Brazilian government agrarian measurement that represents the minimum area of an economically feasible rural property. One Fiscal Module ranges from 5 to 110 ha, depending on the municipality (Landau *et al.*, 2012). Property sizes were defined according to the Federal Law n° 8.629, from 25th February, 1993, as small (≤ 4FM), medium (> 4FM and ≤ 15FM) and large properties (> 15FM). The rural properties used in this study are the ones registered in the CAR database from March 2015.

In order to define accurately the APP width to be restored, it is necessary to calculate the size of each property based on the number of FM within boundary. This is because restoration regulations of APPs are different from APP maps (Tables 4.3, 4.4): the latter is based only on river's width or water body extent, but the former takes into account both the size of the property and a river's width or water body extent. Given that it is not possible to define the APP deficit without property boundaries, in areas not covered by CAR, we established a minimum APP width to restore of 5m from the border of the waterway (based on the minimum required for small properties <1FM); and a maximum APP deficit width of 20m for rivers (based on the requirements for properties >4FM with rivers up to 10-meter width). For water bodies, the buffer width outside CAR was 5-30m APP width from the border of the waterway (Table 4.3, Fig. 4.3). In cases where there is an overlap between properties of different sizes, the APP deficit width is defined based on the largest property. The total area covered by CAR in this study corresponds to 30% of the State (or 35.6 Mha) and the remaining 70% did not present information on properties boundaries.

Table 4.3. Restoration requirements of permanent preservation areas (APPs) under the Brazilian Forest Code (Law N° 12,651, from 25th March 2012) for private properties.

Water courses	Private property sizes	APP deficit width
Rivers and water bodies	small (<1FM)	5 m
	small (>1FM and ≤2FM)	8 m
	small (>2 and ≤4FM)	15 m
Rivers	medium/large (>4FM)	20m
Water bodies	medium/large (>4FM)	30m

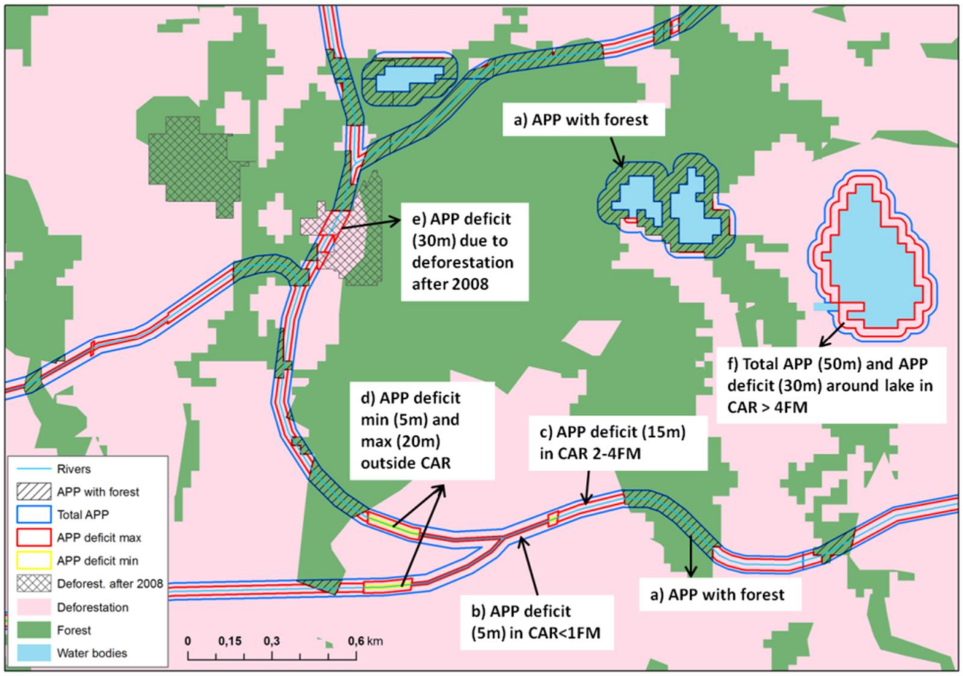

Figure 4.3. Examples of different situations of permanent preservation area (APP) mapped in this study: a) 50-meter APP width of a lake covered by forest cover, which therefore do not need to be restored; b) APP to be restored within a 5-meter buffer around the river, as it is located in CAR<1FM and presents consolidated area (deforestation up to 22nd July 2008); c) APP to be restored within a 15-meter buffer around the river, as it is located in CAR 2-4FM and presents consolidated area; d) APP to be restored within a minimum of 5m and maximum of 20m and presents consolidated area. For APPs outside CAR, the minimum APP deficit is different from the maximum as it is located outside CAR (we cannot say the exactly size of the property); e) APP to be fully restored (30-meter buffer), since deforestation took place after 22nd July 2008; f) Total APP of 50-meter buffer (for water bodies from 1-20ha) and APP to restore within a 30-meter buffer around water bodies located in CAR>4FM. For APPs inside CAR, the minimum APP deficit is the same as the maximum APP. CAR stands for Environmental Rural Property Register and FM for Fiscal Modules.

4.3.5. Data processing and data analysis

The database was processed using the programming platform Python 2.7 and ArcPy package in order to perform APP analysis with the following steps (Fig. 4.1): (i) the original land use and land cover classes were simplified into the classes of deforestation, forest and water bodies (Table 4.4) and combined with CAR and rivers data; (ii) APP was mapped based on the available water course (e.g. rivers and water bodies), following the Forest Code requirements; (iii) rules for restoration were applied to the different water courses (rivers and water bodies) and property sizes, and APP variables (total APP, APP deficit (min and max), APP with forest and consolidated APP (min and max)) were estimated by municipality (Fig 4.3); and (iv) the estimates and related uncertainties of each APP variable were calculated for the 144 municipalities and for Pará as a whole. To estimate uncertainty we used a Partial Least Squares Regression (PLSR), using APP data from the 15 municipalities at both fine and coarse-scale, and then using that model with bootstrapping to calculate APP predictions and associated uncertainties for the remaining municipalities (see section 4.3.5).

Table 4.4. Original and final classes of land use and land cover maps.

Final classes	Original Classes	Source
Deforestation	deforestation, urban areas, commercial reforestation, mining	Imazon
	agriculture, urban areas, mining, all classes of pasture, reforestation	INPE/TerraClass
Forest	degraded forests and regeneration	Imazon
	forest, non-forest, others, secondary forest, unobserved	INPE/TerraClass
Water bodies	water bodies	Imazon
	hydrography	INPE/TerraClass

The original class “unobserved” (due to clouds and shade) from TerraClass (2012) (Embrapa and INPE, 2011) was reclassified as “Forest”, since new deforestation (2008-2014) would be mapped by Prodes in our analysis. However, part of the unobserved area could be old deforestation (before 2008), as TerraClass doesn’t consider the historical data; that is, it doesn’t take into account the previous mapping in subsequent maps. For this reason, an area mapped as deforestated in 2010 could be mapped as unobserved in 2012.

Of the 15 municipalities mapped at 1:25.000, five did not have their area fully analysed because the mapping of land cover and water courses was only focused on the area suitable for CAR registry (areas where CAR is permitted) (Table 4.5). This means that APPs were only estimated for those registerable areas, excluding, for example, protected areas (except Environmental Protected Area – APA in Portuguese) and urban areas. These municipalities are: Brasil Novo, Monte Alegre, Novo Progresso, Novo Repartimento and Santarém. The other ten municipalities had APPs mapped for the whole area (Table 4.5). In order to keep the consistency between fine and coarse-scale data, we excluded the area not suitable for registry from the same 5 municipalities in the 1:100.000 analyses. The area analyzed for the 15 municipalities is shown in Table 4.5.

Table 4.5. Analyzed area of the 15 municipalities at fine and coarse-scale.

Municipality	Area (ha)	Registerable area (ha)	Analyzed area (%)
Abel Figueiredo	61.270	61.270	100
Bom Jesus do Tocantins	280.957	280.957	100
Dom Eliseu	525.312	525.312	100
Jacundá	200.277	200.277	100
Moju	906.982	906.982	100
Paragominas	1.928.561	1.928.561	100
Rondon do Pará	822.347	822.347	100
Santana do Araguaia	1.167.101	1.167.101	100
Tailândia	441.764	441.764	100
Ulianópolis	507.311	507.311	100
Novo Repartimento	1.535.565	1.324.412	86
Santarém	1.785.055	1.398.367	78
Brasil Novo	634.381	478.198	75
Monte Alegre	1.813.703	796.844	44
Novo Progresso	3.827.730	1.121.050	29
Total	**16.438.316**	**11.960.753**	**73**

4.3.6. Estimating APP values and their associated uncertainties

Using the sample dataset (the 15 municipalities), a Partial Least Square Regression Analysis (PLSR) was performed to estimate Rapideye-based APP values (hereafter called "estimated APP") for the 144 municipalities and for Pará (see Table S4.1 for PLSR coefficients), and their associated uncertainties. The PLSR is a multivariate statistical method that allows for regressing a set of correlated response variables with another set of explanatory variables, which can also be strongly correlated. The method was chosen here to allow for estimates of APP variables that account for their multivariate correlation structure, which possibly generates more conservative error variance estimates than if we were to independently regress each pair of APP variables, because APP variables have a strong correlation structure (Fig. 4.5).

The analysis was performed using the package "PLSR" (using the SIMPLS method) from R software (de Jong, 1993). The native R environment provides functions to fit a PLSR model and to predict new observations, but no method is available to estimate confidence intervals for such predictions. For this reason we used 20000 bootstraps to obtain 90% confidence intervals (CI) for the predictions, which were used to represent APP uncertainty (for each variable) for Pará and its municipalities (see supplementary information, section 4.8.3 for more details on bootstrap uncertainty estimates).

4.4. Results

4.4.1. Comparison of fine-scale and coarse-scale data for the 15 municipalities

We mapped 1.4 Mkm of rivers using the fine-scale dataset (Rapideye – 1:25.000) for the 15 municipalities, while 763,000 km were mapped using coarse-scale data (Landsat – 1:100.000), a 45% reduction in relation to the fine data. The scatterplots on Fig. 4.4 show how coarse-scale APP measurements relate to fine-scale measurements on the 15 municipalities. All variables showed a considerable degree of correlation between maps produced at the two scales. Forested APP (4.4b) measured with the two scales show high degree of correspondence and data are close to the 1:1 line, which indicates very similar forest APP area values were measured at the two scales. On the other hand, there is a significant discrepancy between the two datasets for the other variables (4.4c-f), in which coarse-scale measurements heavily underestimate these areas in relation to the corresponding fine-scale measurements, although still exhibiting a strongly linear relationship. In addition, their relationship is weaker, with more variation than for the Forested APP case. Despite the high correlation for Total APP (Fig 4.4a), coarse-scale data underestimates this area compared to fine-scale measurements. All variables, especially APP deficit and consolidated APP showed strong heteroskedasticity, with the variance of fine-scale-based values greatly increasing for values of total APP greater than 40,000 hectares.

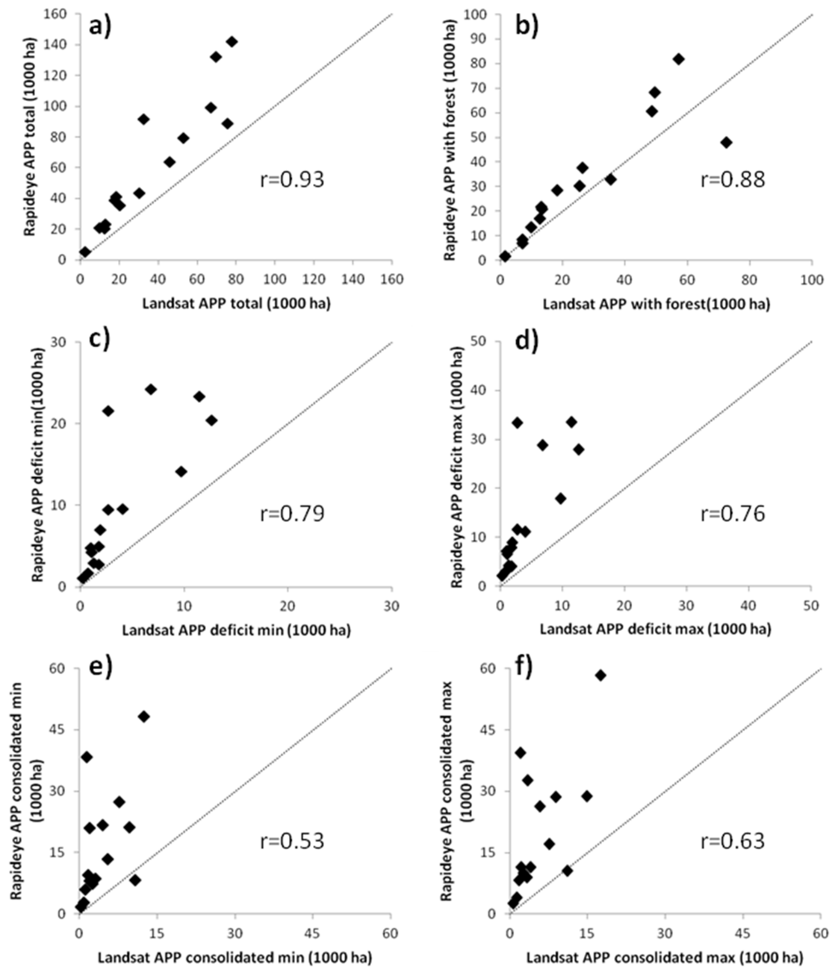

Figure 4.4. Relative APP correlation between fine-scale (Rapideye - 1:25.000) and coarse-scale data (Landsat - 1:100.000) for the 15 municipalities (points in black) and for the APP variables: a) Total APP; b) APP with forest; c) APP to restore (mim); d) APP to restore (max); e) Consolidated APP (min); f) Consolidated APP (max). The 1:1 line represents the expected line if variables presented the same values for Rapideye and Landsat.

4.4.2. The Partial Least Square Regression Analysis

The high degree of heteroskedasticity meant that the models could not be applied to the original data, generating imprecise estimates of APP and excessively inflated confidence intervals, especially for municipalities with lower APP areas. As the error variance seem to increase with APP area, as observed in the sample scatterplots (Fig. 4.4a, b – the points are more disperse around the line when compared to the others), we applied a log transformation to the original variables before performing the analysis. This resulted in more precise estimates and narrower bootstrap confidence intervals. However, it also resulted in estimates of the different APP variables that no longer sum to the total APP, because the variable's correlation structure is changed when logarithms are applied. The change was so that small correlations increased more than larger ones. We suggest that keeping more precise estimates is more relevant than maintaining the consistency of the sum between variables.

Table 4.6 shows the comparison of PLSR estimated values for each APP variable for the sample. The model was estimated using four PLS components, based on cross-validation results. We evaluated the model's fit by comparing the coefficient of variation with the empirical RMSE (root of mean square of errors) for each APP, which is in Table 4.6. Note the higher relative reduction of error variance for the Forested APP when compared to the other variables, indicating that forest had the best fit.

A graphical representation of the model's fit for the different variables is shown in Fig. 4.5. These results suggest that the model is adequate for the purpose of these estimates, and the estimates are significantly more accurate than using the sample mean or coarse-scale data directly.

Table 4.6. PLSR estimated values for each APP variable. RMSE stands for Root of Mean Square of Errors; Sample CV is the Sample Coefficient of Variation; NRMSE is the Normalized root-mean-square deviation; and % Reduction is the relative reduction of error variance.

	Total APP	APP with forest	APP deficit min	APP deficit max	Consolidated APP min	Consolidated APP max
RMSE	9942.0	1749.4	4235.5	5542.0	5055.5	5987.5
Sample CV	0.68	0.74	0.82	0.82	0.83	0.78
NRMSE	0.16	0.06	0.42	0.40	0.31	0.30
% Reduction	0.76	0.93	0.50	0.51	0.62	0.61

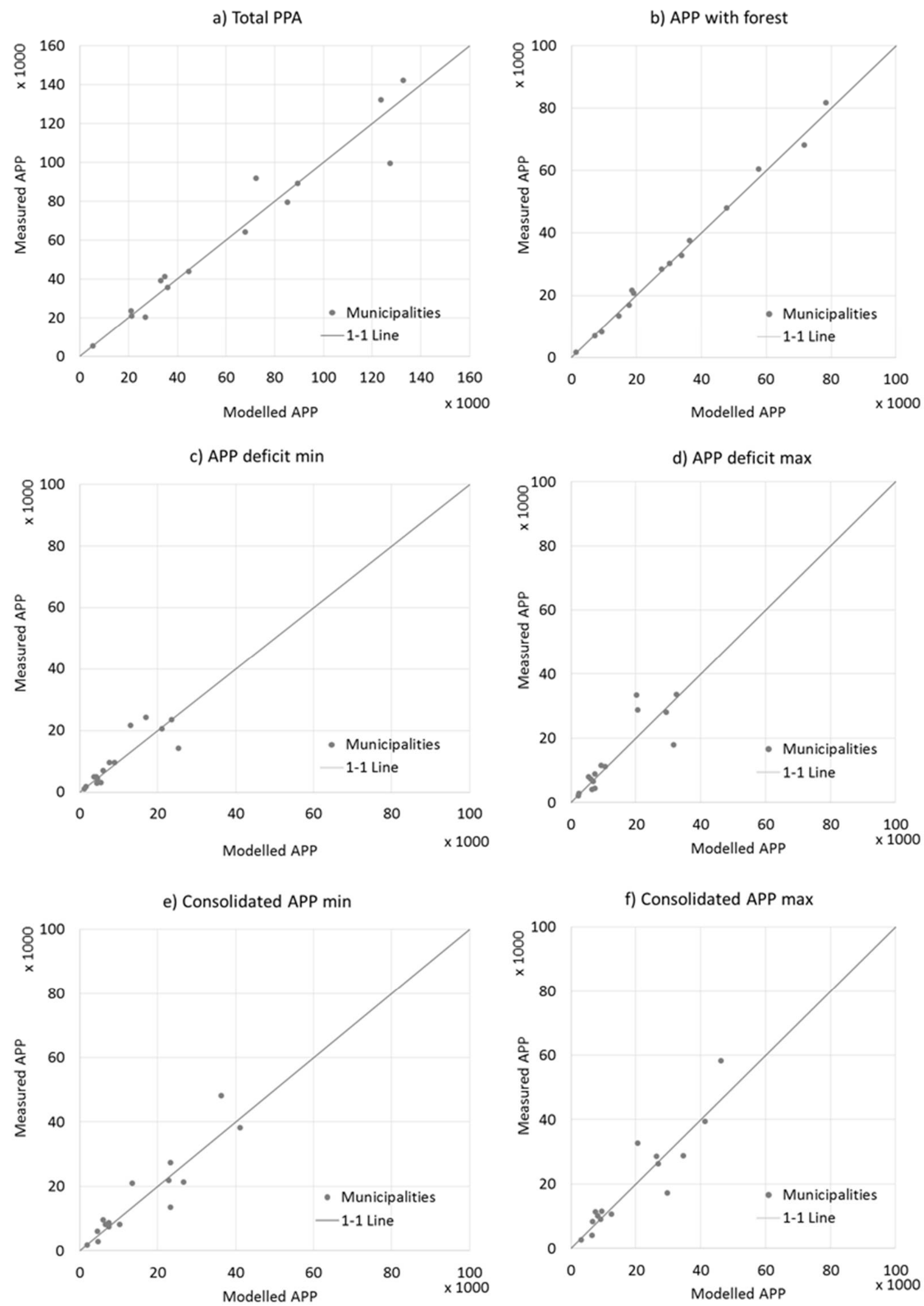

Figure 4.5. Modelled versus Measured APP values of each variable, for the sample of 15 municipalities (points in gray) at fine-scale: a) Total APP; b) APP with forest; c) APP to restore (min); d) APP to restore (max); e) Consolidated APP (min); f) Consolidated APP (max). The 1:1 line represents the expected line if variables presented the same values for Estimated and Measured APP.

4.4.3. Assessing APP variables for all of Pará

The total APP estimated for the 144 municipalities in Pará was 8.7 Mha (5.7 – 12.3), an increase of 41% compared to the estimate based on coarse-scale data (6.1 Mha). APP with forest covered an area of 5.5 Mha (3.3 – 7.9), or 63% of the total APP, and an increase of only 1% in relation to coarse-scale data (5.4 Mha). The minimum APP that needs to be restored by law (deficit min) was 760,000 ha (477,000 – 1.1), or 9% of the total APP, an increase of 134% over the coarse-scale data (325,000 ha). The maximum deficit area that needs to be restored by law was 1Mha (704,000 – 1.5), 12% of the total area and 138% higher than Landsat data (450,000 ha). The minimum extent of the consolidated APP area (cleared but does not need to be restored) was 2.7 Mha (1.5 – 4.1), or 31% of the total area, an increase of 791% on coarse-scale data (300,000 ha). The maximum extent of the consolidated APP area was 3Mha (1.8 – 4.5), or 35% of the total, an increase of 608% on the estimate using coarse-scale data (425,000 ha) (Fig. 4.6).

The APP variables with the highest error (average of the difference between the bootstrap CI bounds and the mean value) to the estimated data were the minimum consolidated area (57%), minimum deficit (up to 51%) and maximum consolidated area (up to 50%). The maximum deficit presented an error of 47%; APP with forest, 46%; and total APP 42%.

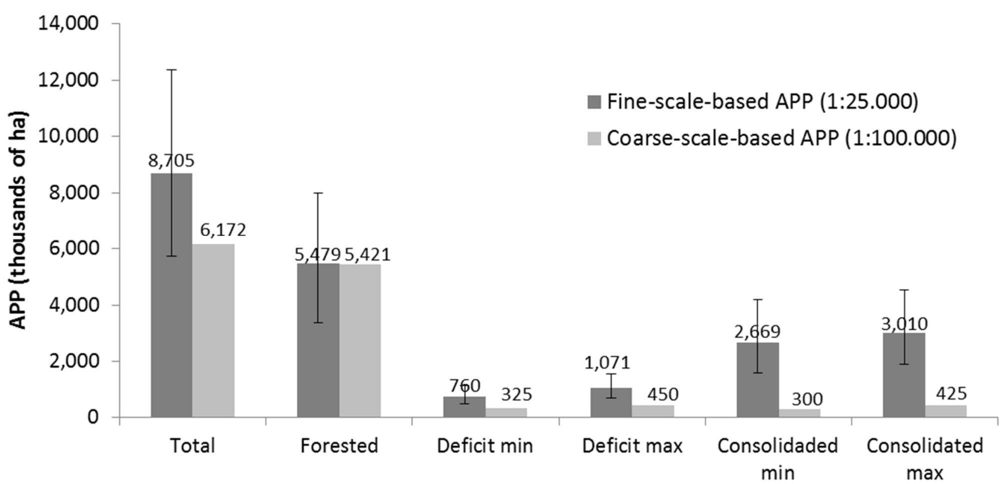

Figure 4.6. Estimated APP based on Rapideye data, and respective CI 90%, and APP sample data calculated from Landsat-based classes for Pará.

4.4.4. Assessing APP across municipalities

The geographical distribution of estimated APP extent per municipality (Fig. 4.7; Table S4.2), shows western Pará with a high concentration of municipalities with relatively forested APPs (Fig. 4.7a,b; Table S4.2), except for the municipalities around the highway BR-230 (Transamazonian), where forest cover was lower. On the other hand, the eastern region and around the Transamazonian, the municipalities had larger amounts of APP deficit (Fig. 4.7a,c,d; Table S4.2). The highest concentration of consolidated APP (deforested areas that are not required to be restored by law) is in western region (Fig. 4.7a, e,f; Table S4.2), where there is the lowest APP to restore.

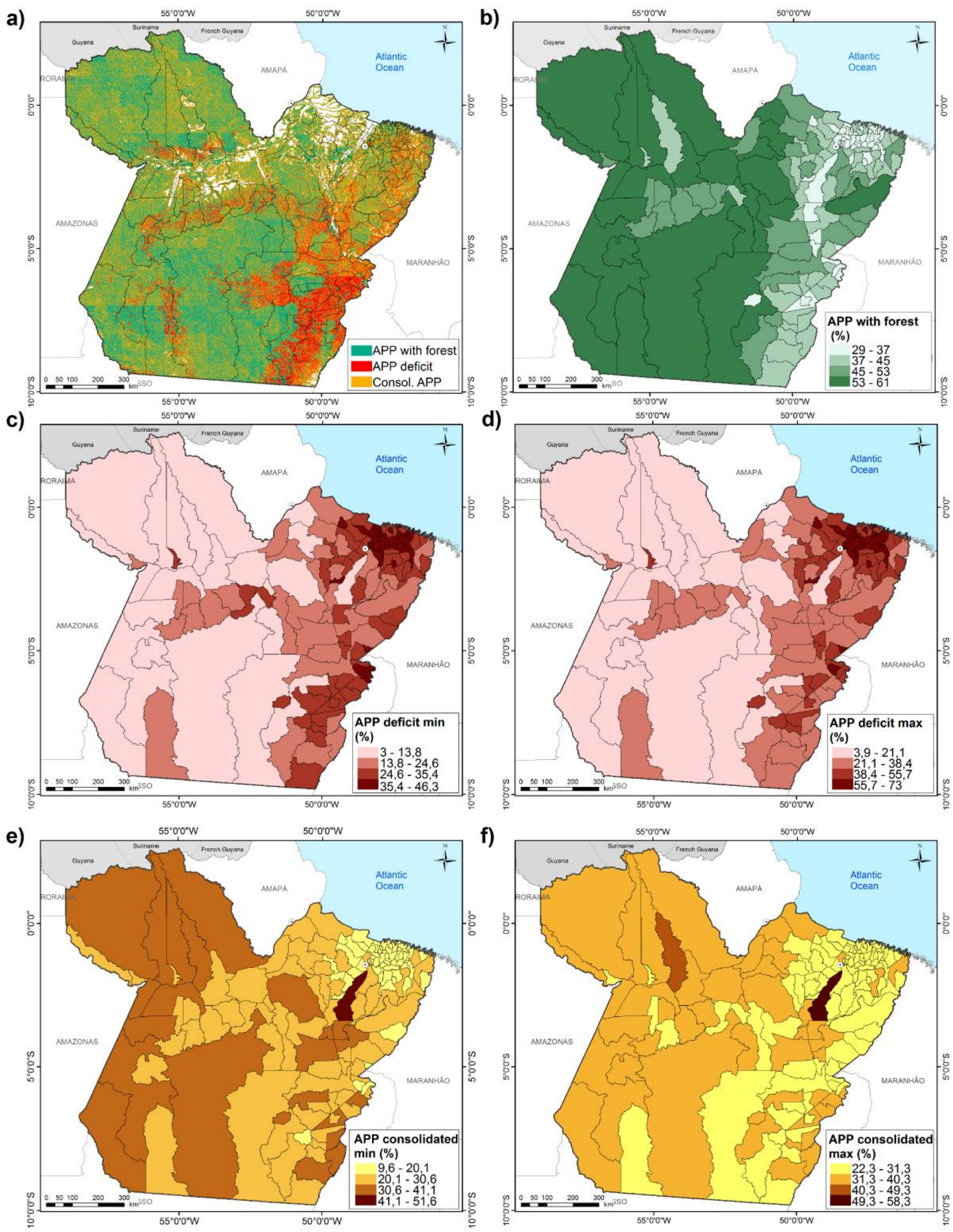

Figure 4.7. Distribution of APP variables across 144 municipalities in Pará. The percentage is relative to the total APP estimated for each municipality: a) distribution of all APP variables across Pará; b) APP

with forest (%); c) APP deficit min (%); d) APP deficit max (%); e) APP consolidated min (%); f) APP consolidated max (%).

4.5. DISCUSSION

4.5.1. Permanent Preservation Areas across Pará and municipalities

The total riparian APP for Pará encompasses an area of 8.7 Mha, or 7% of the State, of which 63% is covered by forest. The area requiring restoration accounts for up to 12% of the total riparian APP, which accounts for only about one-third of the consolidated APP in the state. The minimum consolidated APP (i.e. areas that do not need to be restored following the revision of the Forest Code) accounted for around 31% of the total APP in the state. The APP forest cover approximates the total forest cover for the State, which is c. 65% for Pará (INPE/PRODES, 2015), supporting previous findings that deforestation on private land is largely similar in riparian and non-riparian zones (Nunes *et al.*, 2015). The fact that consolidated APP is more than twice the APP in need of restoration results from the application of the revised Forest Code, as land owners are not obliged to fully restore forests cleared prior to 22nd July 2008. As most of the deforestation in Pará took place before this date, the state has 2.7 Mha of deforested APP that does not need to be restored.

Geographical variation in APP restoration requirements

There is an important within-state variation in APP deficits that need to be restored by law. In 30 municipalities >30% of the APP area needs to be restored, and the implementation and prioritisation of large scale restoration must be planned at municipal level or even finer scales (Fig. 4.7). The pattern of APP coverage and deficits in the study area is directly related to the historical land-use and occupation process in the region. The largest concentration of forested APPs is located in western Pará (Fig. 4.7a), where the agricultural frontier is less advanced and there is the largest coverage of conservation units (e.g. Calha-Norte). In part due to their inaccessible nature, these regions still retain large amounts of forest, except for the municipalities located around the highway BR-230 (Transamazonian – Fig. 4.2) that have lower levels of forest cover, mainly because of historical occupation from rural settlements and other smallholdings, whose main land use is based on agriculture and cattle ranching.

The eastern region has experienced the highest levels of deforestation, mostly due to economic activities such as cattle ranching, practiced in the region since the 1970s when the Brazilian government encouraged immigration and deforestation to guarantee land tenure. Thus, APP deficits are mostly concentrated in this region and along Transamazonian highway (Fig. 4.7b,c; Fig. 4.2). A different behaviour was observed for the distribution of consolidated APPs (Fig. 4.7d,e), which are more concentrated in western region, where deforestation pressure is lower.

Five municipalities out of 144 were not fully analysed due to exclusion of areas that are not suitable for CAR (Table 4.5), and thus present potentially anomalous results. For example, it was expected that Monte Alegre (Fig. 4.2), located in the north-west of the region (Fig. 4.7a), would have a higher concentration of APP with forest as it is mostly covered by forest. However, only the area suitable for registry, which presents the highest rates of deforestation, was analyzed (or 44% of the total area – Table 4.5).

4.5.2. Uncertainties in assessing APPs in Pará

There was a significant difference between the estimated APP variables based on fine-scale data (1:25.000) and the APPs measured with coarse-scale data (1:100.000). For example, we found an increase of 41% of total APP area for fine-scale data when compared to coarse-scale for the 15 municipalities; the estimated APP in need of restoration is up to 138% larger; and the estimated consolidated APP was found to be up to 791% higher than coarse-scale data (Fig 4.6). Unsurprisingly, the highest relative uncertainties were found for the variables with the narrowest APP buffers (minimum APP deficit and minimum consolidated APP) (Fig. 4.6). These findings can be mostly explained by the different scales and data quality used in this study and have profound implications for the scale of the challenge that the implementation of the Forest Code presents.

Taking the 15 municipalities mapped at fine-scale as a reference, the extent of rivers mapped at the fine-scale is almost twice the extent mapped using coarse-scale data, since the density and number of rivers order depend directly on the scale and data quality. Although all variables had shown a considerable degree of correlation between the two scales (Fig. 4.4), the areas of APP deficit and consolidated APP presented a significant discrepancy between the two datasets, and with a high level of variance (Fig.4.4c-f), in which coarse-scale measurements heavily underestimated the extent of these areas. In particular, the areas of APP in need of restoration and the consolidated APPs also presented the highest uncertainties (Fig. 4.6) possibly because the APP width mapped for these variable is smaller than Landsat pixel width (30m), generating lower accuracy maps (Zeilhofer *et al.*, 2011).

Conversely, both mapping scales returned similar estimates for the extent of forested APPs (Fig. 4.4b). This is surprising, as we expected that all variables measured at the fine-scale would be larger when compared to the coarse-scale variables. This result may stem from a potential overestimation of the forest class from TerraClass data (Nunes *et al.*, 2015), in which part of the recent regeneration is classified as secondary forests. Furthermore, for this study, we reclassified the unobserved class into forest, and part of this area is possibly deforested. Although this may have contributed to the uncertainties, its overall effect is likely to have been small: removing the unobserved class from the analysis of the 15 municipalities made no significant changes to the overall results, as unobserved area covered only 7% of the area analysed for the 15 municipalities.

4.5.3. Data and methodological limitations for mapping riparian APPs

Given the limitations of data availability for the whole state of Pará, we had to adjust the application of Forest Code rules in this study in order to estimate the APP area. First, it was not possible to distinguish between rivers of different widths due to scale issues. For example, at 1:100.000 scales, only rivers wider than 80m are mapped as polygons, providing information on river width. Thus, most rivers (up to 80% of total) were mapped as line features and were considered to be up to 10-meter wide. They are: rivers <15-meter wide (at 1:25.000 scale), and rivers <70-meter wide (at 1:100.000 scale). Such limitations likely result in the underestimation of APP extent. Yet, we do not believe that it would make a considerable difference at the state-wide scale of Pará because it is known that small streams (narrower than 10m) comprise ca. 80% of the total channel length in meso-scale Amazon drainage basins and are the most extensive freshwater ecosystem of the Amazon Basin (Junk, 1993; Mcclain and Elsenbeer, 2001; Beighley and Gummadi, 2011).

Second, rivers above 15-meter wide (at fine-scale) and 70-meter wide (at coarse-scale) were mapped as polygons in this study, matching the approach for other types of water bodies (lakes and dams) and providing information on width. However, neither dataset used in this study provided information on the type of water body, and it was not possible to apply different APP rules across larger rivers, lakes and dams. For example, the total APP width for a 50-200-meter wide river is 100m, while for lakes from 1-20 ha is 50m. Thus, all water bodies mapped as polygons were treated as lakes (Tables 4.2, 4.3). While this is likely to result in an underestimation of total APP extent and deficit, it also reflects the limitation of both fine and coarse-scale data available for the study area. Nevertheless, the overall impact is likely to be relatively small as water bodies account for <20% of the APP mapped based on a visual assessment.

Third, we had to define a range of values for mapping the APP deficit given that 80% of the state area was not covered by CAR. For the area outside CAR, we assume that the minimum APP areas in need of restoration is equivalent to what would be needed in the case of a small property (<1FM), and the maximum area to restore is equivalent to what is needed for large properties (>4FM). Likewise, consolidated APPs presented the range of values, given they are also based on the property size and vary with the APP in need of restoration (e.g. the larger the area to be restored, the smaller the consolidated area). The accuracy of APP deficit also depends on reliable and representative CAR registry. Yet, given that 55% of the state is covered by public protected forests, we expect that the main variation in terms of APP in need of restoration and consolidated APPs are within the c.a. 35% of the area suitable for CAR registry in Pará that is not covered by CAR.

4.6. CONCLUSIONS

Riparian APPs are mostly covered by forest in the state of Pará, and their forest cover (63%) closely matches that for all forests at the state-level (65%). Revisions to the

Forest Code in 2012 mean that the area of deforested APP in need of restoration (1 Mha) accounts for only about one-third of the deforested area that does not need to be restored (i.e. the consolidated APPs). This suggests that some important catchments in Pará may not recover fully functioning hydrological systems and or the ecosystem services and biodiversity conservation benefits provided by riparian forests, as around 2.7 Mha of consolidated APP are likely to remain deforested. This lack of riparian forest could have important regional and local impacts on hydrology, stream biogeochemistry, aquatic ecosystems and corridors for wildlife, depending on the fragmentation level of the watershed, extent of deforestation and land use (Biggs *et al.*, 2004). Given the importance of maintaining riparian forests, the shortfall in riparian restoration must be met through incentives rather than regulations. These include national and international programmes offering payments for ecosystem services (such as REDD+), provision of technical support on how to implement restoration, and education programs outlining the direct and indirect benefits from restoration of riparian vegetation (e.g. exploitation of non-timber forest products, agroforestry systems management, payment for ecosystem services and water supply). Although large properties account for most of the deforestation in riparian areas in the region (Nunes *et al.*, 2015), there are good reasons to focus these measures on small properties as they exhibit the highest relative rates of deforestation, include the most vulnerable people with low access to credit and technical support, and were given the largest amnesty in restoring riparian vegetation in the new Forest Code (Table 4.3)

We found that the highest uncertainties in mapping APPs relate to the APP variables that are characterized by narrower widths (APP deficit and consolidated APP), underscoring the importance of scale. The small streams, that account for >80% of total channel length in the Amazon basin, must have a 30-meter APP width on both sides, yet the area that needs to be restored can vary from 5 to 20 meters, depending on the size of the property. Restoration of APPs is a central part of the work by landowners to legalize their economic activities and secure the necessary licenses, e.g. for the sale of agricultural commodities and access to credit. However, land cover and hydrology maps available for the Amazon are limited to 30-meter resolution Landsat imagery, providing 1:100.000 scale maps. As such it is impossible to achieve accurate measurements for small tributaries (Zeilhofer *et al.*, 2011) at this scale. Our work demonstrates that this short-fall of coarse-scale data will lead to a massive underestimation of the effort needed to bring private properties in Pará and elsewhere across the Brazilian Amazon in line with the Forest Code, further weakening the environmental protections that were already scaled back during the 2012 revision of federal legislation (Soares-Filho et al. 2014). Finer resolution land cover data and improved hydrological models are vital for ensuring the accurate implementation of Brazilian legislation and efforts to safeguard the environmental benefits provided by these critically important ecosystems.

4.7. Acknowledgements

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S4.9.1. Geographic database

For the CAR database the scale is not defined as each property may have used different images as a reference. Only after the updated Forest Code, the minimum scale required for properties registered in CAR is 1:50.000 (Brazilian Federal Government, 2012a). At coarse-scale, the rivers were mapped by the Amazon Surveillance System (SIVAM) using Landsat combined with the Space Shuttle Topographic Mission (SRTM) as images of reference. The geographic coordinated system used for all database was Lambert Conformal Conic, datum Sirgas 2000.

S4.9.2. Permanent Preservation Areas mapping

For the water courses mapped by Imazon for the 15 municipalities, we used the 90m-resolution Digital Elevation Model (DEM) of Space Shuttle Topographic Mission (SRTM) in order to map rivers automatically, using ArcGIS 10.0. Second, we performed a fusion between the SRTM and the 5-metre RapidEye images to create an anaglyph product using the software ERDAS Anaglyph tool. Possible mistakes were corrected manually by combining the linear features (rivers) to the anaglyph product and performing a visual analysis. Lakes and dams were manually mapped using the Rapideye images (Souza Jr. *et al.*, 2013).

S4.9.3 Estimating APP values and their associated uncertainties

Because PLSR is a multivariate model, each response variable is estimated as a linear combination of all explanatory variables (Table S4.1).

Table S4.1. PLSR coefficients relating coarse-scale (1:100.000) and fine-scale (1:25.000) APP values (in the log-scale).

Explanatory variables (1:100.000)	Response variables (1:25.000)					
	Total APP	**APP with forest**	**APP deficit min**	**APP deficit max**	**Consolidated APP min**	**Consolidated APP max**
Total APP	-0.440	-1.044	-2.682	-2.738	1.473	0.762
APP with forest	1.056	1.761	2.153	2.189	-0.492	-0.007
APP deficit min	0.786	2.092	3.415	3.012	-1.971	-1.460
APP deficit max	-0.774	-2.277	-3.051	-2.766	2.158	1.565
Consolidated APP min	-1.231	-1.546	-3.660	-4.183	0.770	-0.432
Consolidated APP max	1.531	1.981	4.605	5.235	-0.955	0.506

To obtain bootstrap uncertainty estimates, we initially fited the PLSR model to the sample of 15 Municipalities and calculated their fitted values and residuals. Then, each of the 20,000 bootstrap estimates was obtained as follows:

(i) a bootstrap random sample of 15x1 data row indices was selected, with replacement;

(ii) the residuals were extracted for these 15 data rows, forming a matrix of 15x6 bootstrap residuals.

(iii) each residual column was subtracted from their mean, and the resulting matrix was summed element-by-element to the 15x6 fixed (without resampling) fitted values, resulting in a 15x6 matrix of dependent (RapidEye-based APP) values;

(iv) the bootstrap dependent data matrix was coupled with the 15x6 fixed (without resampling) matrix of controls (Landsat-based APP) and a new PLSR model was fitted;

(v) the resulting model was used to calculate a 144x6 matrix of Municipal bootstrap APP estimates, from the corresponding 144x6 matrix of Landsat-based APP values;

(vi) a 1x6 bootstrap estimate of APP values for Pará was obtained by summing the rows of the 144x6 bootstrap Municipal APP estimates.

This procedure resulted in a pool of 20,000 bootstrap estimates for each of the 6 APP variables, for each Municipality and for Para. Finally, percentiles 5 and 95 were taken from the respective bootstrap pools to represent uncertainty of the APP values for each Municipality, and the State.

S4.9.4. Assessing APP across municipalities

Table S4.2 below shows the estimated APP variables and respective Confidence Interval 90% for the 144 municipalities in Pará.

Table S4. 2. Estimated APP for the 144 municipalities in Pará and for each variable and their respective Confidence Interval of 90% (CI 90%).

Municipalities	Total APP (ha)		Forested APP (ha)		APP deficit min (ha)		APP deficit max (ha)		Consolidated APP min (ha)		Consolidated APP max (ha)	
	Estimated	CI 90%	Estimated	CI 90%	Estimated	CI 90%	Estimated	CI 90%	Estimated	CI 90%	Estimated	CI 90%
ABAETETUBA	12,105	7,434 to 17,877	5,717	3,473 to 8,389	439	193 to 809	831	2,704 to 9,507	4,245	1,971 to 7,523	5,526	2,704 to 9,507
ABEL FIGUEIREDO	5,573	3,568 to 7,995	1,484	912 to 2,159	1,204	625 to 1,993	2,317	1,912 to 5,329	2,127	1,143 to 3,411	3,411	1,912 to 5,329
ACARÁ	30,853	19,690 to 44,316	15,567	9,590 to 22,691	1,366	700 to 2,313	2,317	6,805 to 19,353	9,806	5,217 to 16,027	12,206	6,805 to 19,353
AFUÁ	33,605	18,503 to 54,460	39,379	23,143 to 59,196	202	61 to 466	332	2,987 to 19,124	9,756	3,045 to 21,569	8,919	2,987 to 19,124
ÁGUA AZUL DO NORTE	84,391	55,517 to 119,523	31,519	19,483 to 45,869	22,031	12,852 to 35,127	30,902	20,352 to 48,510	24,249	14,603 to 37,255	32,358	20,352 to 48,510
ALENQUER	156,322	101,764 to 223,421	110,095	68,022 to 160,283	5,238	2,848 to 8,638	7,416	26,292 to 69,765	42,409	23,954 to 68,073	44,801	26,292 to 69,765
ALMEIRIM	380,184	229,795 to 579,953	419,193	251,828 to 623,250	4,835	1,954 to 9,555	6,272	35,503 to 150,615	90,749	37,693 to 173,112	81,064	35,503 to 150,615
ALTAMIRA	1,090,942	664,216 to 1,652,973	838,630	509,345 to 1,239,976	24,853	10,362 to 47,806	32,422	147,861 to 561,109	335,124	149,252 to 618,833	314,263	147,861 to 561,109
ANAJÁS	27,244	15,481 to 42,852	17,730	10,433 to 26,746	294	95 to 631	561	4,387 to 23,083	10,417	3,665 to 21,310	11,634	4,387 to 23,083
ANANINDEUA	3,901	2,176 to 6,234	631	373 to 943	214	66 to 474	648	2,575 to 13,970	4,203	1,477 to 8,715	6,940	2,575 to 13,970
ANAPU	101,634	66,700 to 144,751	73,533	45,484 to 106,917	9,007	5,117 to 14,688	11,049	12,661 to 32,186	18,340	10,590 to 29,011	20,958	12,661 to 32,186
AUGUSTO CORRÊA	10,163	6,061 to 15,469	2,535	1,525 to 3,753	328	128 to 646	850	5,545 to 21,407	8,458	3,730 to 15,570	11,918	5,545 to 21,407
AURORA DO PARÁ	15,920	10,507 to 22,320	7,000	4,338 to 10,123	1,938	1,134 to 2,987	3,095	3,593 to 8,450	4,198	2,509 to 6,321	5,767	3,593 to 8,450
AVEIRO	116,176	74,976 to 166,662	72,291	44,534 to 105,360	3,748	1,953 to 6,272	5,702	22,107 to 60,964	35,234	19,205 to 57,082	38,838	22,107 to 60,964
BAGRE	20,258	11,732 to 31,302	8,908	5,314 to 13,339	314	107 to 649	680	5,277 to 24,476	10,435	3,998 to 20,433	12,910	5,277 to 24,476
BAIÃO	30,985	20,540 to 43,414	12,083	7,513 to 17,540	2,844	1,697 to 4,363	4,836	9,194 to 21,176	10,842	6,644 to 16,278	14,440	9,194 to 21,176
BANNACH	45,176	29,937 to 63,587	16,851	10,423 to 24,504	15,221	9,195 to 23,617	21,127	10,066 to 22,960	11,100	6,826 to 16,636	15,666	10,066 to 22,960
BARCARENA	10,244	5,982 to 15,729	3,098	1,859 to 4,605	197	70 to 399	506	4,542 to 19,144	7,734	3,175 to 14,702	10,422	4,542 to 19,144
BELÉM	9,531	5,358 to 15,219	1,577	928 to 2,369	472	150 to 1,043	1,378	7,054 to 34,554	11,489	4,345 to 23,155	17,663	7,054 to 34,554
BELTERRA	26,887	17,577 to 38,018	14,049	8,688 to 20,380	1,470	825 to 2,347	2,404	5,899 to 14,724	7,867	4,551 to 12,198	9,780	5,899 to 14,724
BENEVIDES	2,193	1,317 to 3,300	531	320 to 781	200	80 to 380	483	870 to 3,431	1,177	503 to 2,161	1,924	870 to 3,431
BOM JESUS DO TOCANTINS	20,800	13,877 to 28,892	8,992	5,587 to 13,024	3,995	2,495 to 5,917	5,921	4,574 to 9,700	5,020	3,189 to 7,209	6,928	4,574 to 9,700
BONITO	5,698	3,650 to 8,173	1,551	953 to 2,254	1,274	667 to 2,101	2,409	1,858 to 5,208	2,068	1,113 to 3,325	3,324	1,858 to 5,208
BRAGANÇA	12,188	7,598 to 17,975	3,154	1,930 to 4,618	797	368 to 1,441	1,798	5,593 to 18,318	7,442	3,673 to 12,843	10,872	5,593 to 18,318
BRASIL NOVO	35,289	23,403 to 49,397	21,018	13,035 to 30,498	6,934	4,205 to 10,617	8,685	4,961 to 11,151	6,066	3,760 to 8,968	7,727	4,961 to 11,151

BREJO GRANDE DO ARAGUAIA	11,589	7,598 to 16,336	3,654	2,255 to 5,317	3,806	2,206 to 5,950	6,145	3,156 to 7,499	3,334	1,972 to 5,036	5,106	3,156 to 7,499
BREU BRANCO	29,264	19,281 to 41,329	9,241	5,697 to 13,419	6,121	3,588 to 9,646	10,109	9,364 to 21,883	10,429	6,324 to 15,774	14,838	9,364 to 21,883
BREVES	56,623	30,707 to 91,364	38,972	22,420 to 59,758	223	58 to 502	468	10,221 to 64,407	30,820	9,489 to 66,537	30,865	10,221 to 64,407
BUJARU	6,289	3,640 to 9,749	2,856	1,704 to 4,250	156	54 to 324	330	1,363 to 6,536	2,542	960 to 5,078	3,376	1,363 to 6,536
CACHOEIRA DO ARARI	8,702	4,253 to 15,049	5,358	2,969 to 8,413	38	7 to 100	92	1,334 to 12,879	4,730	1,080 to 11,785	5,350	1,334 to 12,879
CACHOEIRA DO PIRIÁ	21,574	14,264 to 30,188	10,163	6,308 to 14,705	3,077	1,817 to 4,749	4,573	4,268 to 9,903	4,991	3,009 to 7,495	6,772	4,268 to 9,903
CAMETÁ	22,786	13,586 to 34,642	7,249	4,390 to 10,716	474	182 to 936	1,127	9,697 to 37,764	16,230	7,091 to 29,985	21,077	9,697 to 37,764
CANAÃ DOS CARAJÁS	42,802	28,740 to 59,610	18,336	11,385 to 26,559	10,437	6,653 to 15,481	14,438	9,259 to 19,374	10,228	6,621 to 14,766	13,753	9,259 to 19,374
CAPANEMA	6,418	3,968 to 9,518	1,343	819 to 1,962	969	435 to 1,769	2,175	2,956 to 10,358	3,668	1,734 to 6,463	5,996	2,956 to 10,358
CAPITÃO POÇO	20,103	13,211 to 28,353	6,418	3,967 to 9,315	2,864	1,666 to 4,485	5,079	6,688 to 16,288	7,564	4,502 to 11,556	10,860	6,688 to 16,288
CASTANHAL	7,875	4,960 to 11,448	2,649	1,626 to 3,862	598	290 to 1,035	1,196	2,434 to 7,535	3,155	1,591 to 5,328	4,600	2,434 to 7,535
CHAVES	22,466	13,122 to 34,718	15,429	9,233 to 22,829	195	72 to 394	389	4,552 to 21,001	10,839	4,186 to 21,332	11,036	4,552 to 21,001
COLARES	2,074	1,087 to 3,452	1,027	591 to 1,564	17	4 to 43	46	447 to 3,301	1,170	326 to 2,743	1,467	447 to 3,301
CONCEIÇÃO DO ARAGUAIA	65,740	43,218 to 93,343	22,549	13,913 to 32,732	11,355	6,588 to 18,167	17,879	19,904 to 47,994	23,807	14,295 to 36,722	31,797	19,904 to 47,994
CONCÓRDIA DO PARÁ	4,661	2,734 to 7,144	2,011	1,206 to 2,978	161	59 to 328	337	1,022 to 4,612	1,766	692 to 3,444	2,437	1,022 to 4,612
CUMARU DO NORTE	199,783	131,491 to 283,604	99,342	61,291 to 144,273	39,785	23,332 to 63,827	49,129	35,479 to 85,388	46,950	28,132 to 72,659	56,634	35,479 to 85,388
CURIONÓPOLIS	28,460	18,297 to 41,005	7,583	4,632 to 11,151	10,483	5,510 to 17,752	17,058	9,104 to 23,862	10,164	5,723 to 16,153	15,413	9,104 to 23,862
CURRALINHO	22,700	13,070 to 35,434	14,642	8,663 to 21,955	427	146 to 906	755	3,231 to 16,103	7,029	2,575 to 14,230	8,239	3,231 to 16,103
CURUÁ	16,433	10,635 to 23,404	7,786	4,805 to 11,328	921	495 to 1,504	1,605	3,909 to 10,402	5,189	2,869 to 8,259	6,730	3,909 to 10,402
CURUÇÁ	8,776	5,295 to 13,223	4,706	2,847 to 6,934	154	64 to 298	321	2,094 to 8,296	3,844	1,647 to 7,196	4,563	2,094 to 8,296
DOM ELISEU	37,446	24,937 to 52,297	20,706	12,854 to 29,991	8,981	5,556 to 13,627	11,221	5,541 to 12,192	6,557	4,105 to 9,612	8,536	5,541 to 12,192
ELDORADO DOS CARAJÁS	31,764	20,422 to 45,624	8,890	5,400 to 13,136	12,776	6,704 to 21,694	19,997	9,439 to 24,815	10,702	6,031 to 17,068	15,980	9,439 to 24,815
FARO	73,129	45,449 to 107,906	47,600	28,929 to 70,014	1,017	449 to 1,837	1,778	14,891 to 50,259	28,169	13,401 to 49,100	29,804	14,891 to 50,259
FLORESTA DO ARAGUAIA	40,883	26,745 to 58,298	12,372	7,611 to 17,967	7,613	4,314 to 12,335	12,807	13,841 to 34,447	16,070	9,442 to 25,036	22,610	13,841 to 34,447
GARRAFÃO DO NORTE	12,211	7,887 to 17,464	3,677	2,269 to 5,337	1,517	821 to 2,472	2,888	4,193 to 11,451	4,918	2,718 to 7,883	7,301	4,193 to 11,451
GOIANÉSIA DO PARÁ	62,229	41,388 to 87,513	23,662	14,663 to 34,342	7,900	4,818 to 12,157	12,486	18,167 to 41,279	21,505	13,407 to 32,246	28,070	18,167 to 41,279
GURUPÁ	29,786	16,720 to 47,753	31,916	18,805 to 47,870	240	77 to 538	390	2,727 to 16,372	8,077	2,649 to 17,436	7,828	2,727 to 16,372
IGARAPÉ-AÇU	7,033	4,460 to 10,151	2,981	1,831 to 4,340	640	319 to 1,100	1,133	1,553 to 4,642	2,023	1,039 to 3,367	2,875	1,553 to 4,642

IGARAPÉ-MIRI	13,498	8,146 to 20,284	7,528	4,529 to 11,122	399	164 to 774	722	2,398 to 9,474	4,206	1,815 to 7,804	5,249	2,398 to 9,474
INHANGAPI	4,027	2,380 to 6,129	1,352	815 to 2,000	145	55 to 287	339	1,288 to 5,384	2,036	837 to 3,847	2,934	1,288 to 5,384
IPIXUNA DO PARÁ	42,654	28,480 to 59,513	18,194	11,314 to 26,352	4,886	3,020 to 7,343	7,584	10,799 to 23,833	12,582	7,942 to 18,549	16,508	10,799 to 23,833
IRITUIA	12,041	7,824 to 17,085	3,688	2,275 to 5,356	1,698	943 to 2,712	3,151	4,040 to 10,503	4,598	2,614 to 7,216	6,831	4,040 to 10,503
ITAITUBA	455,461	286,262 to 669,249	250,716	153,793 to 366,655	15,318	7,304 to 27,410	22,780	95,481 to 306,659	172,900	86,873 to 298,808	182,018	95,481 to 306,659
ITUPIRANGA	65,861	44,216 to 91,931	31,292	19,407 to 45,332	14,779	9,455 to 22,043	19,354	12,718 to 26,732	14,640	9,492 to 21,233	18,896	12,718 to 26,732
JACAREACANGA	323,637	198,531 to 483,619	212,556	128,917 to 313,851	4,808	2,012 to 8,975	7,640	61,660 to 219,832	127,255	58,408 to 228,526	127,078	61,660 to 219,832
JACUNDÁ	24,209	16,084 to 33,769	9,040	5,610 to 13,108	5,556	3,427 to 8,385	8,505	6,291 to 13,692	6,878	4,333 to 10,075	9,614	6,291 to 13,692
JURUTI	71,349	45,505 to 103,541	31,577	19,376 to 46,154	1,889	947 to 3,223	3,541	22,993 to 64,628	34,928	18,958 to 56,948	40,666	22,993 to 64,628
LIMOEIRO DO AJURU	8,644	4,347 to 14,742	6,281	3,521 to 9,783	36	7 to 92	82	1,176 to 10,604	4,134	997 to 10,161	4,464	1,176 to 10,604
MÃE DO RIO	4,573	2,890 to 6,615	1,251	766 to 1,822	711	351 to 1,206	1,436	1,564 to 4,739	1,838	935 to 3,040	2,927	1,564 to 4,739
MAGALHÃES BARATA	3,802	2,080 to 6,161	2,445	1,430 to 3,674	73	21 to 170	143	486 to 3,120	1,162	363 to 2,586	1,450	486 to 3,120
MARABÁ	118,341	78,839 to 166,013	59,426	36,830 to 86,210	24,260	15,100 to 37,353	30,499	21,369 to 47,152	26,218	16,598 to 39,061	32,482	21,369 to 47,152
MARACANÃ	8,456	5,122 to 12,748	4,947	2,983 to 7,279	224	93 to 437	417	1,504 to 5,996	2,680	1,153 to 5,027	3,305	1,504 to 5,996
MARAPANIM	7,944	4,841 to 11,874	4,311	2,617 to 6,338	183	79 to 348	364	1,733 to 6,573	3,019	1,337 to 5,584	3,685	1,733 to 6,573
MARITUBA	1,370	761 to 2,182	202	119 to 302	153	46 to 332	455	804 to 4,533	1,214	411 to 2,528	2,227	804 to 4,533
MEDICILÂNDIA	52,162	35,178 to 72,329	27,116	16,847 to 39,255	5,739	3,665 to 8,398	8,165	10,881 to 22,418	12,888	8,455 to 18,513	16,007	10,881 to 22,418
MELGAÇO	33,402	18,640 to 53,691	35,781	20,945 to 53,915	313	98 to 708	493	2,770 to 17,397	8,280	2,624 to 17,979	8,188	2,770 to 17,397
MOCAJUBA	6,798	3,969 to 10,469	1,469	881 to 2,178	281	102 to 574	760	3,765 to 16,472	5,814	2,362 to 11,170	8,791	3,765 to 16,472
MOJU	42,798	27,506 to 61,832	25,221	15,520 to 36,792	3,506	1,804 to 5,859	5,092	7,592 to 21,426	11,889	6,344 to 19,312	13,604	7,592 to 21,426
MOJUÍ DOS CAMPOS	40,848	27,108 to 57,198	19,694	12,227 to 28,557	2,601	1,555 to 3,953	4,213	10,255 to 23,215	12,881	7,954 to 19,231	15,982	10,255 to 23,215
MONTE ALEGRE	72,579	48,184 to 102,037	38,055	23,566 to 55,219	5,218	3,138 to 8,003	7,835	17,067 to 38,397	22,625	14,153 to 33,906	26,290	17,067 to 38,397
MUANÁ	21,442	11,600 to 34,825	6,419	3,762 to 9,713	227	61 to 520	616	8,940 to 53,077	20,112	6,511 to 43,094	25,852	8,940 to 53,077
NOVA ESPERANÇA DO PIRIÁ	18,984	12,455 to 26,829	6,771	4,193 to 9,824	2,288	1,314 to 3,621	3,967	5,476 to 13,738	6,393	3,723 to 9,911	9,060	5,476 to 13,738
NOVA IPIXUNA	13,611	9,013 to 18,973	5,463	3,394 to 7,907	3,170	1,923 to 4,784	4,825	3,068 to 6,836	3,352	2,066 to 4,903	4,797	3,068 to 6,836
NOVA TIMBOTEUA	5,943	3,787 to 8,542	2,297	1,412 to 3,339	715	367 to 1,206	1,274	1,400 to 4,040	1,727	903 to 2,821	2,546	1,400 to 4,040
NOVO PROGRESSO	124,354	82,844 to 174,850	68,553	42,424 to 99,414	22,496	14,016 to 34,925	27,567	20,285 to 44,697	25,340	16,020 to 37,668	30,826	20,285 to 44,697
NOVO REPARTIMENTO	134,123	88,738 to 189,301	58,338	36,056 to 84,775	23,307	13,909 to 36,730	31,869	30,297 to 70,992	38,321	23,408 to 58,740	47,538	30,297 to 70,992

ÓBIDOS	188,829	120,792 to 273,655	123,900	76,139 to 181,034	4,721	2,350 to 8,086	7,127	35,318 to 103,017	60,919	32,219 to 101,314	63,941	35,318 to 103,017
OEIRAS DO PARÁ	17,031	10,423 to 25,377	6,687	4,073 to 9,824	572	243 to 1,077	1,164	4,830 to 17,537	7,617	3,464 to 13,667	10,082	4,830 to 17,537
ORIXIMINÁ	542,544	320,618 to 834,529	508,461	303,095 to 761,097	4,045	1,466 to 8,135	5,993	69,633 to 314,280	189,951	75,065 to 369,089	166,648	69,633 to 314,280
OURÉM	4,868	3,067 to 7,069	1,289	790 to 1,876	753	367 to 1,287	1,537	1,708 to 5,304	2,025	1,018 to 3,386	3,244	1,708 to 5,304
OURILÂNDIA DO NORTE	153,796	101,808 to 217,875	107,893	66,848 to 156,645	12,919	7,707 to 20,493	15,887	21,648 to 51,273	30,734	18,659 to 47,303	34,193	21,648 to 51,273
PACAJÁ	102,875	68,462 to 144,518	63,730	39,512 to 92,458	16,628	10,295 to 25,719	19,910	14,714 to 32,556	18,747	11,802 to 27,897	22,456	14,714 to 32,556
PALESTINA DO PARÁ	9,783	6,293 to 13,989	2,505	1,539 to 3,664	2,740	1,447 to 4,524	5,011	3,482 to 9,192	3,793	2,119 to 5,975	5,990	3,482 to 9,192
PARAGOMINAS	125,941	83,905 to 177,259	80,477	49,886 to 116,779	17,339	10,680 to 26,897	20,792	18,143 to 40,437	23,733	14,923 to 35,557	27,722	18,143 to 40,437
PARAUAPEBAS	72,069	45,921 to 104,918	24,840	15,287 to 36,209	3,570	1,805 to 6,222	6,756	26,271 to 78,156	37,746	20,056 to 63,063	47,734	26,271 to 78,156
PAU D'ARCO	22,538	14,827 to 31,846	6,871	4,247 to 9,986	4,749	2,767 to 7,450	8,043	7,286 to 17,397	8,000	4,788 to 12,165	11,709	7,286 to 17,397
PEIXE-BOI	5,142	3,202 to 7,564	1,234	753 to 1,801	636	293 to 1,125	1,401	2,120 to 7,072	2,622	1,267 to 4,515	4,196	2,120 to 7,072
PIÇARRA	43,820	28,642 to 62,279	13,917	8,544 to 20,307	12,954	7,380 to 20,944	19,793	12,531 to 30,189	14,153	8,416 to 21,865	20,113	12,531 to 30,189
PLACAS	60,743	40,788 to 84,628	34,335	21,339 to 49,780	7,128	4,472 to 10,682	9,588	10,855 to 23,027	13,203	8,520 to 19,233	16,210	10,855 to 23,027
PONTA DE PEDRAS	9,599	4,960 to 15,974	3,411	1,937 to 5,280	46	10 to 112	139	3,733 to 25,455	9,697	2,778 to 21,576	11,843	3,733 to 25,455
PORTEL	152,944	96,507 to 223,524	96,114	58,840 to 140,829	3,977	1,888 to 7,022	6,128	27,968 to 87,668	49,224	24,720 to 83,501	53,217	27,968 to 87,668
PORTO DE MOZ	70,657	44,611 to 103,334	50,360	30,824 to 73,804	2,380	1,152 to 4,248	3,475	10,069 to 31,975	17,288	8,652 to 29,502	19,260	10,069 to 31,975
PRAINHA	92,340	60,660 to 130,663	55,469	34,358 to 80,485	4,405	2,509 to 7,021	6,486	17,789 to 43,716	25,474	15,006 to 39,454	29,064	17,789 to 43,716
PRIMAVERA	3,223	1,994 to 4,736	1,199	731 to 1,753	302	138 to 546	588	781 to 2,667	1,049	493 to 1,840	1,573	781 to 2,667
QUATIPURU	3,779	2,237 to 5,742	1,380	829 to 2,037	90	35 to 179	221	1,323 to 5,512	2,235	924 to 4,274	2,992	1,323 to 5,512
REDENÇÃO	44,220	29,202 to 62,317	15,405	9,506 to 22,425	13,481	8,050 to 21,034	19,663	11,290 to 25,890	12,535	7,685 to 18,879	17,630	11,290 to 25,890
RIO MARIA	48,031	31,584 to 67,953	16,971	10,432 to 24,811	18,251	10,622 to 29,153	25,489	11,179 to 26,615	12,700	7,610 to 19,447	17,887	11,179 to 26,615
RONDON DO PARÁ	61,572	41,239 to 85,904	27,940	17,369 to 40,491	7,370	4,610 to 11,022	10,853	14,401 to 31,294	17,057	10,883 to 25,087	21,791	14,401 to 31,294
RURÓPOLIS	57,804	38,853 to 80,323	29,620	18,423 to 42,888	5,444	3,432 to 8,042	7,934	12,616 to 26,490	15,225	9,867 to 22,095	18,769	12,616 to 26,490
SALINÓPOLIS	3,761	2,280 to 5,629	2,183	1,325 to 3,199	328	141 to 634	532	503 to 1,928	798	351 to 1,468	1,081	503 to 1,928
SALVATERRA	4,216	2,557 to 6,309	1,332	808 to 1,963	171	71 to 319	404	1,588 to 5,794	2,306	1,040 to 4,169	3,314	1,588 to 5,794
SANTA BÁRBARA DO PARÁ	2,727	1,491 to 4,389	884	519 to 1,332	47	13 to 107	129	907 to 5,309	1,818	592 to 3,893	2,582	907 to 5,309
SANTA CRUZ DO ARARI	2,537	1,038 to 4,946	3,615	1,886 to 5,860	22	2 to 74	37	65 to 1,532	468	55 to 1,470	498	65 to 1,532
SANTA ISABEL DO PARÁ	4,990	3,043 to 7,428	2,108	1,280 to 3,093	327	140 to 617	620	1,054 to 3,930	1,560	699 to 2,832	2,229	1,054 to 3,930

SANTA LUZIA DO PARÁ	9,323	5,929 to 13,486	2,475	1,520 to 3,598	1,155	582 to 1,967	2,359	3,576 to 10,793	4,312	2,240 to 7,187	6,616	3,576 to 10,793
SANTA MARIA DAS BARREIRAS	109,643	71,811 to 155,986	41,743	25,788 to 60,750	23,790	13,627 to 38,415	33,646	27,104 to 66,108	33,678	19,974 to 52,350	43,629	27,104 to 66,108
SANTA MARIA DO PARÁ	4,236	2,581 to 6,335	884	537 to 1,295	541	229 to 1,008	1,274	1,946 to 7,297	2,496	1,119 to 4,496	4,137	1,946 to 7,297
SANTANA DO ARAGUAIA	91,337	59,697 to 130,050	32,723	20,177 to 47,666	24,804	14,035 to 40,275	35,064	22,545 to 55,793	27,350	16,080 to 42,723	36,688	22,545 to 55,793
SANTARÉM	101,964	65,076 to 147,256	57,398	35,244 to 83,761	2,280	1,126 to 3,858	3,871	24,473 to 69,798	39,952	21,332 to 65,723	43,812	24,473 to 69,798
SANTARÉM NOVO	2,475	1,458 to 3,774	753	453 to 1,113	134	50 to 266	314	780 to 3,373	1,189	477 to 2,268	1,825	780 to 3,373
SANTO ANTÔNIO DO TAUÁ	4,325	2,451 to 6,775	1,424	846 to 2,124	103	32 to 219	257	1,402 to 7,104	2,545	920 to 5,170	3,613	1,402 to 7,104
SÃO CAETANO DE ODIVELAS	4,174	2,412 to 6,485	1,961	1,171 to 2,908	62	22 to 131	147	1,130 to 5,469	2,283	854 to 4,595	2,802	1,130 to 5,469
SÃO DOMINGOS DO ARAGUAIA	10,657	6,943 to 15,017	3,983	2,461 to 5,788	5,242	3,034 to 8,340	7,417	1,998 to 5,014	2,186	1,255 to 3,367	3,346	1,998 to 5,014
SÃO DOMINGOS DO CAPIM	13,419	8,597 to 19,240	6,357	3,915 to 9,265	888	459 to 1,499	1,521	2,883 to 8,225	3,881	2,066 to 6,333	5,169	2,883 to 8,225
SÃO FÉLIX DO XINGU	773,036	496,671 to 1,130,693	554,515	340,508 to 809,577	72,204	37,560 to 127,542	79,778	94,477 to 276,495	165,655	87,985 to 278,112	169,217	94,477 to 276,495
SÃO FRANCISCO DO PARÁ	3,809	2,356 to 5,600	1,177	718 to 1,719	397	181 to 711	815	1,134 to 3,845	1,466	692 to 2,539	2,280	1,134 to 3,845
SÃO GERALDO DO ARAGUAIA	41,852	27,486 to 59,214	13,897	8,552 to 20,252	11,672	6,800 to 18,564	17,711	11,703 to 27,373	13,156	7,965 to 20,054	18,485	11,703 to 27,373
SÃO JOÃO DA PONTA	2,503	1,329 to 4,147	1,840	1,068 to 2,773	91	25 to 224	156	206 to 1,520	522	148 to 1,216	674	206 to 1,520
SÃO JOÃO DE PIRABAS	8,302	5,210 to 12,112	3,967	2,425 to 5,799	306	146 to 543	595	2,103 to 6,764	3,197	1,574 to 5,501	4,045	2,103 to 6,764
SÃO JOÃO DO ARAGUAIA	11,722	7,735 to 16,398	4,208	2,608 to 6,102	2,062	1,218 to 3,146	3,469	3,270 to 7,515	3,584	2,167 to 5,317	5,182	3,270 to 7,515
SÃO MIGUEL DO GUAMÁ	11,042	7,142 to 15,671	4,078	2,517 to 5,927	991	538 to 1,605	1,826	3,196 to 8,446	3,876	2,162 to 6,127	5,488	3,196 to 8,446
SÃO SEBASTIÃO DA BOA VISTA	11,174	6,732 to 16,793	8,220	4,975 to 12,080	831	351 to 1,623	1,170	1,064 to 4,312	1,881	801 to 3,531	2,365	1,064 to 4,312
SAPUCAIA	15,991	10,247 to 23,019	3,956	2,421 to 5,802	5,813	3,009 to 9,847	10,079	5,477 to 14,803	5,994	3,314 to 9,590	9,484	5,477 to 14,803
SENADOR JOSÉ PORFÍRIO	118,493	74,976 to 173,704	90,270	55,113 to 132,347	3,839	1,848 to 6,875	5,333	15,564 to 50,152	27,963	13,860 to 48,114	30,010	15,564 to 50,152
SOURE	8,667	4,581 to 14,276	2,093	1,202 to 3,202	62	15 to 150	212	5,889 to 36,529	13,577	4,259 to 29,483	17,379	5,889 to 36,529
TAILÂNDIA	26,322	17,486 to 36,695	13,917	8,642 to 20,166	4,857	2,951 to 7,377	6,548	4,347 to 9,618	5,080	3,160 to 7,446	6,728	4,347 to 9,618
TERRA ALTA	1,695	962 to 2,658	589	350 to 875	90	30 to 193	205	401 to 2,077	681	243 to 1,392	1,047	401 to 2,077
TERRA SANTA	24,246	14,448 to 37,026	23,144	13,947 to 34,152	870	352 to 1,748	1,184	1,963 to 8,710	4,188	1,697 to 8,093	4,619	1,963 to 8,710
TOMÉ-AÇU	30,684	19,714 to 44,066	17,316	10,685 to 25,203	1,772	925 to 3,009	2,748	5,446 to 15,313	7,800	4,194 to 12,760	9,685	5,446 to 15,313
TRACUATEUA	5,871	3,719 to 8,471	2,034	1,248 to 2,981	420	210 to 715	860	1,952 to 5,780	2,542	1,317 to 4,211	3,592	1,952 to 5,780
TRAIRÃO	112,144	73,230 to 159,935	64,685	40,037 to 94,089	5,218	2,862 to 8,523	7,756	22,059 to 57,240	32,525	18,524 to 51,411	37,191	22,059 to 57,240
TUCUMÃ	22,425	14,249 to 32,510	5,538	3,336 to 8,228	8,376	4,096 to 14,662	14,270	7,814 to 21,709	8,915	4,844 to 14,540	13,705	7,814 to 21,709

TUCURUÍ	42,279	28,104 to 59,386	15,713	9,725 to 22,783	4,584	2,764 to 7,048	7,671	13,498 to 30,454	15,857	9,925 to 23,747	20,805	13,498 to 30,454
ULIANÓPOLIS	40,686	27,020 to 57,005	21,230	13,183 to 30,749	12,406	7,713 to 18,977	15,246	6,058 to 13,501	7,073	4,407 to 10,438	9,383	6,058 to 13,501
URUARÁ	88,715	59,629 to 123,400	49,464	30,686 to 71,687	11,741	7,503 to 17,547	15,326	16,167 to 33,582	19,723	12,918 to 28,570	23,791	16,167 to 33,582
VIGIA	3,216	1,853 to 4,994	1,051	629 to 1,564	79	27 to 163	201	1,127 to 5,251	1,940	741 to 3,812	2,755	1,127 to 5,251
VISEU	41,146	27,145 to 58,135	15,976	9,925 to 23,196	3,029	1,764 to 4,751	5,265	12,797 to 30,835	15,838	9,508 to 24,268	20,581	12,797 to 30,835
VITÓRIA DO XINGU	32,064	21,463 to 44,524	16,048	9,969 to 23,233	5,654	3,561 to 8,358	7,787	6,007 to 12,577	6,832	4,394 to 9,824	8,992	6,007 to 12,577
XINGUARA	42,153	26,542 to 61,839	10,217	6,211 to 15,038	10,803	5,152 to 19,353	19,031	16,075 to 47,403	19,799	10,384 to 33,047	29,184	16,075 to 47,403

S4.9.5 Supplementary References

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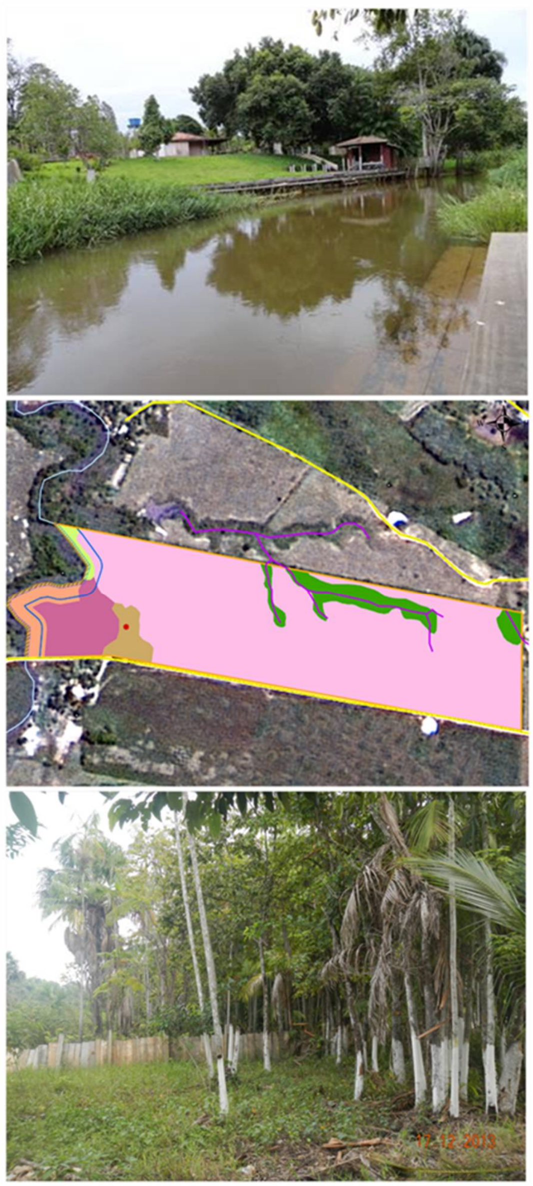
Chapter 5

5. Concluding remarks



5.1. KEY FINDINGS

This thesis focuses on advancing our understanding of some of the key challenges and opportunities facing forest conservation and restoration in the Brazilian Amazon, including private protected forests that have been illegally deforested in the past. I focused on the Legal Reserve and Permanent Preservation Areas that are key instruments of the Brazilian environmental law responsible for conserving forests in private properties. To do this, I combined remote sensing and GIS techniques to apply the legal framework of the Forest Code to assess environmental performance and evaluate patterns of compliance. The key findings are outlined below:

5.1.1. Historical deforestation in riparian forests in the eastern Brazilian Amazon (Chapter 2)

Research questions: (i) does the temporal pattern of deforestation within RAPPs (riparian permanent preservation areas) follow the same pattern of forest loss observed in areas outside RAPPs? In other words, do RAPPs offer any additional protection to riparian forest? (ii) In areas that have already been cleared, is the level of forest regeneration inside RAPPs similar to that observed outside RAPPs? And (iii) do environmental liabilities differ between specific types of land tenure, including private properties, agrarian reform settlements, indigenous land or untitled (unregistered) private lands?

I found no evidence that riparian forests have been more effectively protected than non-riparian forests in Paragominas. Deforestation of riparian forests followed the same general trend as deforestation elsewhere in the municipality. Moreover, in relative terms deforestation was actually greater inside versus outside RAPPs in 2010, indicating a widespread lack of compliance with environmental legislation. This failure of compliance was further illustrated by a lack of evidence for higher levels of regeneration in riparian zones, where, according to the Brazilian Constitution (Article 225, §3°; http://english.tse.jus.br/arquivos/federal-constitution), property owners have been obliged since 1988 to restore areas that have been cleared illegally. I also found that the planning and implementation of restoration activities need to focus on both large and small properties. This is because larger properties (> 825 ha) contributed the most to the total deforestation of RAPPs in Paragominas in 2010, because they cover 69% of the total area of Paragominas. Conversely, small (≤ 55–220 ha) and medium (220–825 ha) properties, and settlements were the land tenure classes with the highest proportion of RAPP (relative to their total areas) in a deforested state in 2010.

5.1.2. Legal forest surplus and deficit of the state of Pará (Chapter 3)

Research questions: (i) What is the Legal Reserve (LR) deficit and surplus for the entire state of Pará?; (ii) What proportion of the total surplus can be considered deforestable versus compensation-only surplus? (iii) How is the total deficit and surplus for the state distributed across properties of different sizes?; and (iv) What is the capacity of each municipality to compensate its LR deficit within the same or adjacent municipalities?

In this chapter, I show that the total LR surplus I assessed in Pará is more than five times the total area of deficit (12.6 million ha versus 2.3 million), indicating that Pará could contribute substantially towards the compensation of the LR deficit for other states (e.g. Mato Grosso) within the same biome. However, I also found that the vast majority (90%) of surplus in Pará is compensation-only surplus that cannot be legally deforested. I also found that the surplus and deficit of LR areas varies significantly among different actors. Medium and large properties contributed the most to the deficit area (22.6% and 12.9%, respectively), while agrarian reform settlements were the most balanced in terms of having both compensation-only surplus and deforestable surplus. The distribution of deficit and surplus across municipalities also plays an important role for the implementation of public policies. Of the municipalities that have properties in deficit, 111 could compensate deficit with surplus areas within the same municipality, while all the remaining 32 could compensate from surplus areas in one or more of the neighboring municipalities, indicating compensation can always take place close to the source of the deficit.

5.1.3. The conservation status of riparian forests of the state of Pará (Chapter 4)

Research questions: (i) What is the current status of riparian APPs across the state, including their total extent, forested extent and total area that is required to be restored by law? (ii) What uncertainty and potential bias is introduced into assessments of riparian forest when using coarse or fine-resolution land-cover and hydrological data?

Chapter 4 shows that riparian APPs are mostly covered by forest in the state of Pará, and their forest cover (63%) closely matches that for all forests at the state-level (65%). However, the Forest Code regulations mean that the area in need of restoration (1 Mha) accounts for only about one-third of the deforested area that does not need to be restored. This suggests that some important catchments in Pará may not achieve fully recover hydrological and ecological functions, as around 2.7 Mha of consolidated APP are likely to remain deforested. We also found that the highest data uncertainties are found for APP variables characterised by narrower widths (APP deficit and consolidated APP), suggesting that the main source of the uncertainties is scale-related. Land cover and hydrology maps available for the Amazon are limited to 30-meter resolution Landsat imagery, providing 1:100.000 scale maps. Given that small streams account for >80% of total channel length in Amazon basin, it is impossible to achieve accurate APP measurements for small tributaries at this scale, severely undermining efforts to implement the Forest Code.

5.2. Future research needs

5.2.1. Accurate cartographic products

This thesis identified a number of key challenges that need to be addressed in order to obtain reliable assessments of environmental liabilities, facilitate law enforcement and monitoring and guide large-scale public policies for the conservation and restoration of LR and APPs. Some examples are listed below:

(i) The accuracy of APP maps in the Amazon is limited by the quality (or lack) of mapping data in the region, including high resolution and recent digital elevation models to inform improved hydrological models and quantification of the width of water courses (Silva *et al.*, 2013) and, critically, the almost complete lack of field validation data to establish whether water courses predicted by digital elevation models actually exist on the ground. For example, our analysis may have overestimated the current distribution of water courses, as small streams predicted by this approach may only be dry topographic depressions on the ground, or they may be depressions that only have above-ground water flow during episodes of very high precipitation (Chapter 2). Conversely, I may also have underestimated RAPPs, as the DEM resolution (90 meters) used in this study may have been insufficient to map smaller or transient streams that exist in the field but were not projected by the water courses mapping approach (see Chapter 2). The accuracy of APP maps can also be affected by the scale: we found that the highest data uncertainties are relative to the variables with narrower width (APP deficit and consolidated APP), suggesting that the main source of the uncertainties is scale-related. However, land cover and hydrology maps available for the Amazon are limited to 30-meter resolution Landsat imagery, providing 1:100.000 scale maps - impossible to achieve accurate measurements for small tributaries (see Chapter 4).

(ii) The lack of representative and reliable georeferenced register of private properties (CAR) remains a major barrier to effective implementation of environmental regulations in the Amazon region. This was apparent in Chapter 3, where it was necessary to develop a multi-step process to resolve inconsistencies in the CAR database. Even though the state of Pará has the most advanced Brazilian state in registering its private properties in the CAR system (Whately and Campanili, 2013), many municipalities still present low areas of registered private lands, such as Quatipuru (3%) and Augusto Corrêa (5%) (SEMA/Imazon, 2016). Furthermore, the Secretary of State for the Environment estimates that only 4,000 of approximately 100,000 properties registered in CAR in the state have been validated on the ground (Ausier, 2013). Thus, the CAR database presents many uncertainties regarding overlapping property boundaries, and the definition of legal reserve areas, productive land and APPs, all of which severely complicate the task of identifying areas in need of restoration.

(iii) Official data on land use and land cover for the Amazon are not always accurate, despite being the best available source of information at large spatial scales. In

Chapter 2, it was not possible to estimate the deficit in APP due to the lack of detailed (1:50.000) and reliable hydrological maps for Pará, which are required by law in Brazil. For a more complete diagnosis of LR deficit in the State, as required by law, more detailed mapping and assessment of APPs is essential to estimate the potential for forest restoration in Pará. Moreover, in Chapter 3, I have estimated an area of 1 Mha detected by TerraClass as deforestation in 2008 and as secondary forest in 2010. In a 2-year-window it is unlikely the development of secondary forest, defined by TerraClass as forests at an advanced stage of regeneration, suggesting a substantial overestimate of the extent of older secondary forests.

5.2.2. Uncertainty in environmental regulations

In this thesis, I identify several instances where the complexity of Brazilian environmental laws have led to misunderstandings and controversies among different sectors (for example government, NGOs and farmers) on how to enforce the law and estimate legal liabilities (LR and APP deficits) (Ellinger and Barreto, 2012; Vale *et al.*, 2014; Vieira *et al*., 2014). For example, the opportunities given to the landowner to reduce LR deficit are flexible and this makes it difficult to define or predict the alternative compliance pathways (i.e. blends of on-farm restoration and compensation from different regions) that are likely to be adopted and therefore their implications for the conservation of remaining forests (Chapter 3).

Chapter 2 highlights the pervasive lack of clarity about what is legally considered to be a RAPP under Brazilian law. This, in turn, undermines confidence in defining the conservation and restoration responsibilities of a landowner in order to become compliant with the law. For example, it remains unclear whether RAPPs should also be enforced in areas with irregular flows that may only contain water during severe storms or for a limited time in the peak of the wet season. Often these specific decisions are left to the subjective (and therefore variable and inconsistent) judgment of local environment agency enforcement officers.

Another challenge to implementing the restoration actions necessary to achieve environmental compliance is that land owners often do not have access to sufficient financial resources or technical support to implement the work, as highlighted in Chapters 2, 3 and 4. Where credit lines are available to support restoration activities (for example through PRONAF [*Programa Nacional de Fortalecimento da Agricultura Familiar*] or *Fundo Amazônia*), individuals are often unaware that they exist, or how to access them (Cardoso, 2011). In situations where individuals are able to access credit, information on costs and technical assistance is often poor or non-existent, and the logistical support necessary to actually implement restoration is often lacking (such as provision of seeds, access to nurseries and technical support in planting efforts).

5.2.3. Recommendations for achieving legal compliance

In Chapter 3 we identified the potential for LR deficits to be addressed through compensation in nearby areas. Considering that 77% of the municipalities can compensate their deficit within the same municipality, this offers an important opportunity for the government to guide (whether through regulation or incentives) compensation and restoration action to the same or neighboring municipalities in order to maintain regionally important ecosystem services and strengthen biodiversity conservation within the region. In the municipalities that have no choice but to compensate their LR deficit in other municipalities, it will be important to incentivize compensation within the same area of endemism.

Second, this thesis highlights the importance of prioritizing conservation efforts in properties that have a deforestable surplus, even when such forests are degraded. To improve the potential conservation dividends from the compensation-only surplus, that makes up the vast majority of the legal reserve surplus across the state, the government could use the compensation regulatory system as a mechanism to avoid further deforestation of standing forests, e.g. through clear incentives or conditions to prioritize compensation with the remaining deforestable surplus. We also highlighted the huge untapped opportunity to encourage efforts to avoid forest degradation and promote rehabilitation efforts in areas that are severely degraded. In addition to conservation actions to protect forest that cannot be degraded, there could be advantages of encouraging local forest restoration in municipalities that would otherwise have to compensate remotely.

Finally, a general recommendation from Chapters 2, 3 and 4 would be to give greater priority to economic incentives and education programs over further command and control actions, especially if compliance is to be improved amongst more vulnerable smallholders (Brancalion *et al.*, 2012). This is specially applied to APPs where the management of natural recourses is more limited compared to LRs. Other economic incentives, such as payment for ecosystem services (PES) and Environmental Reserve Quotas (CRA), are poorly established, partly as a consequence of the lack of federal governmental regulation of such incentives (Santos *et al.*, 2012). Although large properties account for most of the deforestation in riparian areas in the region (Nunes *et al.*, 2015), there are good reasons to focus these measures on small properties as they exhibit the highest relative rates of deforestation, include the most vulnerable people with low access to credit and technical support, and were given the largest amnesty in restoring riparian vegetation.

5.3. Concluding remarks on research needs

While Brazil has one of the most complex and advanced set of environmental laws, our results are relevant to the governance of forests on private lands in many other tropical forests nations. However, many challenges and barriers must be addressed in order to achieve legal compliance of Brazil´s widely lauded flagship environmental legislation. In summary, there is an urgent need to improve the availability, quality and scale of remote sensing and GIS products in the Amazon. As required by law, reliable assessments of APPs and LR at the level of individual properties requires detailed and reliable databases, including validated CAR, hydrological and land cover maps and digital elevation models. Access to financial resources or technical support is also vital for achieving legal compliance, especially among smallholders and in APPs where restoration can be particularly technically challenging. Improved awareness on how to enforce the law and estimate legal liabilities (LR and APP deficits) is key in order to reduce misunderstandings and controversies among different sectors (for example government, NGOs and farmers).

Finally, there is a wide range of measures that fall outside the existing legal framework of the Forest Code that could significantly improve efforts to protect biodiversity and avoid further deforestation, such as: incentives to encourage forest restoration of riparian areas, even where it is no longer legally obligated; education programs outlining the direct and indirect benefits from riparian vegetation; national and international programmes offering payments for ecosystem services in land that can be legally deforested; use of off-farm compensation mechanisms to avoid deforestation through clear incentives or conditions to prioritize compensation with the remaining deforestable surplus; encourage compensation to happen as locally as possible to guarantee the protection of biodiversity in forests with similar structure and ecological characteristics as where the deficit occurred; and encourage restoration of highly fragmented forest areas. Thus, the work of this thesis in improving our understanding of the requirements and potential for forest compensation and restoration, through the mechanisms of APP and LR, offers a key advance for achieving environmental compliance in Pará and elsewhere in the Brazilian Amazon and the wider tropics.

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