EVALUATING THE FOREST PROTECTION BENEFITS OF COSTA RICA'S PAYMENT FOR ENVIRONMENTAL SERVICES PROGRAM

by

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A Dissertation
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DEDICATION

This is dedicated to my parents, who raised me and have supported me for all these years, waiting for this time to arrive.

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I would like to thank FONAFIFO for their work implementing and maintaining data on the PSA program; special thanks to Javier Fernandez, Alberto Mendez, Gilmar Navarrete, and Carmen Roldán, at FONAFIFO, for providing me with PSA datasets.

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LIST OF ABBREVIATIONS

CEOS .... Centre for Earth Observation Sciences (at the University of Alberta)
CR05 ....Costa Rica 2005 (a datum)
CRTM05 ....Costa Rica Transverse Mercator 2005 (a projected coordinate system)
CTO.. Certifiable Tradeable Offset
FONAFIFO ....*Fondo Nacional de Financiamiento Forestal* (Costa Rica)
FONAFIFO 2018 ....2018 dataset from FONAFIFO of 2011-2018 PSA contracts
FONAFIFO 2020 ....2020 dataset from FONAFIFO of 2011-2019 PSA contracts
FAO...United Nations Food and Agriculture Organization
FAOSTAT....................Food and Agriculture Organization Corporate Statistical Database
GIS .... geographic information system or geographic information software
GLAD .... Global Land Analysis and Discovery (at UMD)
GRS...Geodetic Reference System
INEC ....*Instituto Nacional de Estadística y Censos* (Costa Rica)
MINAE .... *Ministerio de Ambiente y Energía* (Costa Rica)
NASA... National Aeronautics and Space Administration (USA)
PES..................................... payments for ecosystem services (the general policy concept)
PSA .... *Pago de Servicios Ambientales* (the specific policy in Costa Rica)
SINAC....................................... *Sistema Nacional de Áreas de Conservación* (Costa Rica)
UMD ....the University of Maryland
USGS .... United States Geological Survey
WGS...World Geodetic Survey

ABSTRACT

EVALUATING THE FOREST PROTECTION BENEFITS OF COSTA RICA'S PAYMENT FOR ENVIRONMENTAL SERVICES PROGRAM

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George Mason University, 2020

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Costa Rica's Pago de Servicios Ambientales program is a "payments for ecosystem services" program, compensating landowners for activities such as protecting forests. Its effects on forest protection in Costa Rica are examined here, by examining the incidence of forest loss outside of and within PSA areas using a global dataset of gross forest loss. Several PSA contracts and two non-PSA points were examined in detail to demonstrate their regional variability and the use of Google Earth imagery to examine forest cover. Gross forest loss outside PSA in 2010-2017 was found to be low, 0.379% per year, which PSA further reduced.

CHAPTER 1: INTRODUCTION

This dissertation aims to evaluate the impacts of Costa Rica's *Pago de Servicios Ambientales* (PSA), or Payment for Environmental Services, program. This is a type of "payments for ecosystem services" (PES) policy that compensates landowners for forest conservation, among other activities, in order to protect and enhance tropical forests and the resources they provide.

This dissertation is structured as follows:

- This first chapter offers an introduction to the topic as a whole and its various parts, starting with the importance of tropical forest conservation, an explanation of the "payments for ecosystem services" concept, and an overview of Costa Rica's forest policy history, including the PSA program.
- The second chapter offers a literature review, examining other research that has analyzed the forest cover benefits of PSA protection contracts.
- The third chapter tries to estimate deforestation rate outside of PSA contracts. A map of random points covering the whole country was generated, and inapplicable points were excluded. Then, annual gross deforestation rates were calculated using the remaining points, and using a global gross forest loss dataset, during the time period 2010-2018.

- The fourth chapter looks at the PSA contracts themselves, as well as their pixel coverage, using that same global gross forest loss dataset to check for instances of deforested pixels in PSA coverage areas.
- The fifth chapter serves as a case study to demonstrate a regional analysis of a subset of PSA contract locations, displaying the regional variability of its effects in direct comparison to the national-level assessment of the previous chapter by reusing its methodology. It also examines one PSA contract and two non-PSA points in finer spatial detail using Google Earth imagery, demonstrating the use of this imagery in verifying/elaborating on local conditions.
- The sixth chapter discusses the results of the previous three chapters, explains a number of caveats, and highlights some future directions for research.
- The appendix presents an analysis using an alternate dataset that the author could not properly align in GIS software.

1.1. The role of forests and the need for tropical forest conservation

Forests serve a variety of important functions. Some of these functions have local and regional impacts, such as regulating and filtering the supply of water, providing various forest products (such as fruit and timber), and direct human uses (such as art, tourism, recreation, and other cultural and religious functions). Forests also help sequester carbon and are a haven for biodiversity – two impacts that are seen as having worldwide impacts. Such functions are like services provided by forests to humanity, and so (such as in Loft 2011) they have been termed "ecosystem services", also known as "environmental services".

Carbon sequestration is a key part of the effort to mitigate climate change. Carbon dioxide (CO_2) is an important greenhouse gas (GHG) implicated in anthropogenic global warming and climate change (Lal 2008), and while a large amount of CO_2 emissions are from the burning of fossil fuels for energy and transportation needs, deforestation is a meaningfully significant contributor as well, estimated at approximately 6 to 17% (Baccini et al. 2012) of total global emissions of CO_2, with emission rate estimates ranging from 1.0 Pg C / yr (tropical forests and land use change, per Baccini et al. 2012) to about 2.9 Pg C / yr (gross tropical deforestation, per Pan et al. 2011). Forests store carbon both in their plant growth as their soils, and deforestation can contribute to the loss of both carbon pools. Meanwhile, preservation of existing forests, by preventing deforestation, is seen as a relatively low-cost, easy-to-accomplish method of reducing emissions of CO_2, in comparison to some other strategies such as transitioning energy and transportation systems away from the burning of fossil fuels.

Biodiversity is also a valuable resource, for everything from maintaining well-functioning and resilient ecosystems to bioprospecting to ecotourism. Forests, particularly tropical forests, are known for being home to significant biodiversity (Gaston 2010, Bush & Hoogiemstra 2005), giving an additional reason for preserving existing tropical forests, especially old-growth forests. Costa Rica, the subject of this dissertation, is particularly prominent in this regard, with an estimated 6% of the world's known species (de Camino et al. 2000).

For these and other reasons, forest protection is often considered a useful focus for conservation efforts. Methods for addressing forest protection include devising environmental policies to mandate and/or incentivize forest preservation.

This goal is seen as especially important in developing countries, where most tropical forests are located: many of these countries are undergoing economic development, during which they may make intense use of or change to natural resources, such as clearing forests extensively for agricultural, residential, and resource extraction land uses. This pathway has been conceptualized as an "environmental Kuznets curve" (Culas 2012), an environmental degradation analogue of the curve that models economic development as increasing social inequity before subsequently decreasing it. The endpoint can be conceptualized as a "forest transition" (Redo et al. 2012), wherein a developing country stops experiencing net deforestation and begins experiencing net forest gain, often due to factors like urbanization, changes in major industries, development/wealth leading to greater environmental concern. In these terms, the goal of forest protection policies could be seen as reducing the peak of the environmental Kuznets curve by accelerating progress toward a forest transition.

Efforts to achieve this goal include the United Nations' REDD+ framework (short for Reducing Emissions from Deforestation and Forest Degradation, plus Forest Enhancement), which aims to quantify and monitor forests in developing countries to help protect and regrow them. This framework offers resources such as international funding pathways and logistical support for forest protection programs.

In Costa Rica, this framework has been used to support the implementation of a legal framework that recognizes the ecosystem services provided by forests and aims to compensate owners of privately-owned forest land for these services. Costa Rica is a small country in Central America known today as a notable ecotourism destination and as a world leader on environmental and sustainable development policies. But in the past, it experienced a trend of declining forest cover. To address this, a landmark law was passed in 1996 – Law No. 7575, which set up the program known as the Payment for Environmental Services (*Pago de Servicios Ambientales*, hereafter abbreviated PSA), the first national-level implementation of a payments for ecosystem services (PES) program in the tropics (Arriagada et al. 2011, Cameron 2015).

1.2 The payments for ecosystem services (PES) concept, and Costa Rica's *Pago de Servicios Ambientales* (PSA) program

The idea of "payments for ecosystem services" (sometimes referred to by other terms such as "payments for environmental services") is to compensate owners of a property for "ecosystem services" (also known as "environmental services") that their property provides. For example, the owner of a forest could be compensated for the fact that a water user downstream of the forest in the same watershed benefits from the forest's cleaning and regulating the water supply. (A fuller list of ecosystem services provided by forests, including examples, can be found in Loft 2011.)

Environmental policy instruments can be grouped into three types: "command-and-control regulations, economic or market-based instruments, and educational instruments" (Fonseca & Drummond 2015). The first is direct regulation of activities with environmental impacts; the second is using financial incentives to attempt to correct market failures that produce environmental problems; the third educates relevant members of the public about the environmental issue in order to change their behavior. A PES program is, at least in theory, an example of the second type, since (to use terminology from economics) it aims to correct a free-rider problem, the underprovision of a public good, by assigning financial value to it – value that may convince a landowner to choose an alternate land use. Further discussion of the economic theory can be found in various papers, such as Robalino & Pfaff (2013) and Robalino et al. (2008). (See especially their price/quantity graphs, illustrating the range of land values that PES could influence.)

Consistent with this understanding, Costa Rica's PSA is – at least superficially – an example of the second kind, as it aims to give financial compensation to landowners for protecting forests (or planting trees or allowing regeneration), on the basis that they provide four ecosystem services as enumerated in the law. In practice, however, the PSA is accompanied by a command-and-control regulation -- a prohibition on soil use change. Furthermore, it is reported to have the effect of raising awareness amongst the public about the value of forests and forest conversation, so it may also act as an educational instrument (as mentioned in Sills et al. 2008). Therefore, Sierra and Russman (2006) expect PSA and other PES programs to be "an intermediary stage in the formation of true markets for environmental services, in which beneficiaries of the services and goods provided by specific habitats would pay land owners for their conservation". Besides, it may be easier to make a market for some environmental services/goods, such as water quality/availability, than for others, such as biodiversity.

Efforts to evaluate Costa Rica's PSA cannot divorce it from its accompanying ban on soil use change. The two together seem redundant if both are perfectly enforced, but the argument is generally made (Sánchez-Azofeifa et al. 2007, Pagiola 2008, Pfaff et al. 2008, Daniels et al. 2010) that PSA may allow the ban to be politically palatable and enforceable, by offering a direct practical benefit for compliance, so that the "carrot" (PSA payments) and "stick" (the ban) exist simultaneously, and they also raise public awareness. However (as Porras et al. 2013 point out) there exist other interpretations, e.g. that the PSA is a “rebranding” of existing conservation incentives (Matulis 2012), or that it is a way to make up for poor enforcement capability (Porras et al. 2013).

PES in general may also have secondary effects beyond areas under contract. For forest protection efforts, these secondary effects are termed "leakage" and "spill-overs" (e.g. in Sills et al. 2008). "Leakage" refers to when an activity that causes deforestation is prevented in one place only to occur elsewhere instead, reducing positive effect of a policy. Leakage may occur by shifting an activity that clears forest from one part of a property to another part, or from one property to another property -- such as clearing a different plot of land for pasture or timber. In contrast, "spill-overs" refer to protection of uncontracted forest that owners or land-users preserve because the policy was implemented elsewhere, likely nearby. Spill-overs may occur when landowners/users become aware of the value and/or need of preserving forests or when they choose to preserve forests in anticipation of contracting the land under PES when funds become available – a relevant consideration since Costa Rica's PSA has at times had far more applicants than funding (Sierra & Russman 2006).

1.3 History of Costa Rica's forest cover and forest policy

Costa Rica is a relatively small country in Central America, spanning approximately 51,000 square kilometers. As mentioned earlier, it is known today for its natural beauty, its biodiversity (it is home to 6% of the worlds' known species, including a number of endemic species (de Camino et al. 2000), while just being 0.5% of the world's land area), its ecotourism opportunities, and its leadership in environmental and sustainable development policies among developing countries. Costa Rica’s varied landscape hosts a variety of forest ecosystems, as shown in Fig. 1.1, a map of the Holdridge life zones represented in the country (reproduced from Bolaños et al. 2005). Most of the country is in forest life zones of various kinds, from rainforests (purples) to wet and moist forests (greens) to dry forests (yellows), with a wide range of elevations due to the mountains running through the center of the country. (The remaining colors, consisting of blues, are mainly water, plus a patch of bright blue representing páramo, which is basically a high-altitude grassland.)

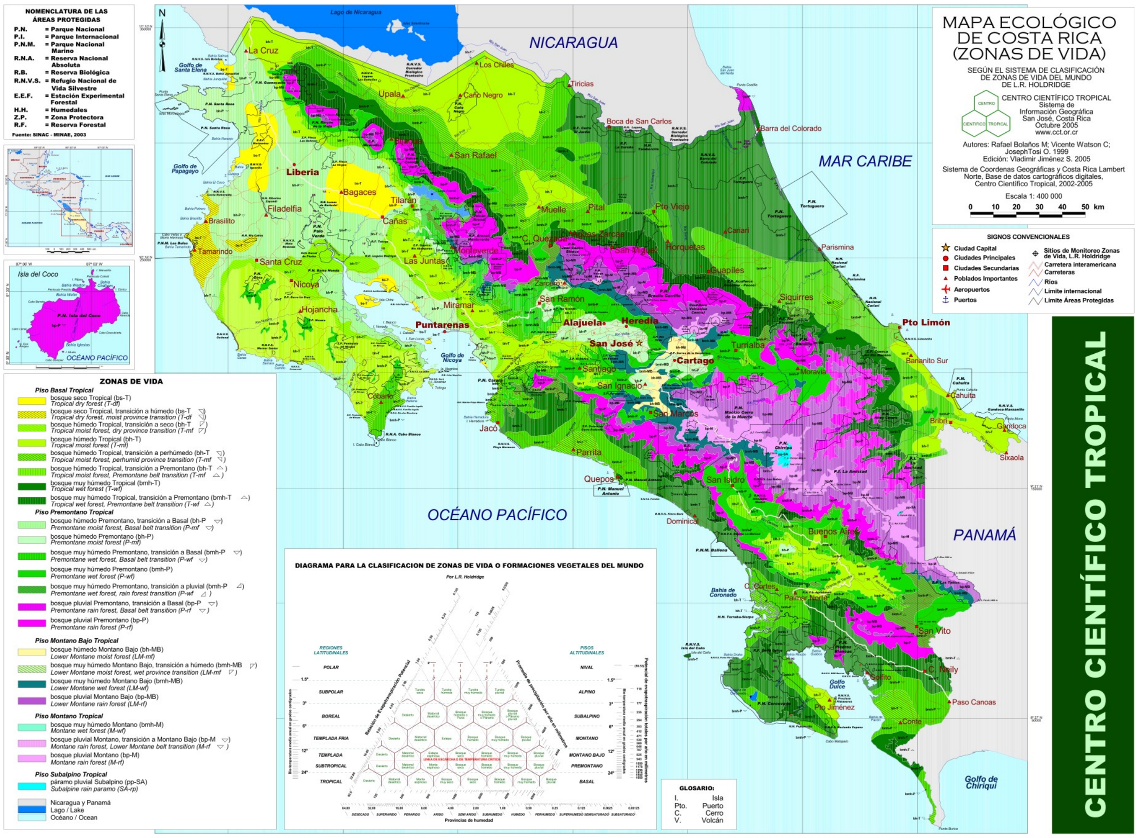

Figure 1.1: Map of Holdridge life zones of Costa Rica (Bolaños et al. 2005)

In the past, up until about the 1970s, Costa Rica's forest cover was in decline, at first due to gradual colonization of the area and later due to the expansion of cash drops such as coffee, bananas, tobacco, sugarcane, and oil palm, as well as timber harvesting and cattle ranching; of these, the most relevant deforestation drivers in the 20th century were bananas, coffee, and cattle ranching (Evans 1999). Furthermore, other circumstances favored such land use change, such as the development of roads (making timber extraction more viable) government policies supporting the coffee and cattle industries (in the 1950s and 1970s, respectively), and even a "denuncio" policy (in the 1930s and 1940s) that granted property rights in return for clearing forest (Nygren 1995).

Forest cover is widely reported to have fallen from about 75% to about 21% during the period 1940 to 1987, and then reported to have risen again to around 51% by the year 2005 (Murillo et al. 2011). This fall and rise in forest cover has been "repeatedly published" in what has been described facetiously as a "forest striptease" (Kleinn et al. 2002) and is reproduced in Fig. 1.2 (from Robalino et al. 2011, which credits FONAFIFO, see below for explanation of acronym), but actual assessments of forest cover have spanned a range of values, as shown in Fig. 1.3 (reproduced from Kleinn et al. 2002), where each circular dot represents "a published forest cover figure" and each diamond dot represents a forest cover estimate according to FAOSTAT. Kleinn et al. (2002) also contains a set of figures nearly identical to Fig. 1.2, and notes that the data source for these estimates changes from aerial photography for the first three maps (1940, 1950, 1961) to Landsat Multi-Spectral Scanner (MSS) imagery for the next two (1977, 1983) then to Landsat Thematic Mapper imagery for the next one (1997). Furthermore, Kleinn et al. (2002) remarks that interpretation methods have affected the forest cover statistic reported.

Forest cover maps have been made and officially published since the 1940s (as reported in Kleinn et al. 2002); some recent maps have been made by the National Forestry Financing Fund (*Fondo Nacional de Financiamento Forestal*, or FONAFIFO). Methodological differences are responsible from some of the observed change in forest cover – for example, the sharp rise (and to some extent the dramatic decline preceding it) may be due to more accurate measurement of forest resources, especially in the dry forest areas of Guanacaste, which tend to be defoliated and less easy to detect during months of the year that have less cloud cover (i.e. the dry season) (Kleinn et al. 2002). But there is a downward trend that Kleinn et al. (2002) observe in the various studies done of forest cover, lasting from 1940 to "about" 1990, as plotted in Fig. 1.3. Furthermore, Sanchez-Azofeifa et al. (2001) studied the difference between 1986 and 1991 forest cover – using Landsat 5 Thematic Mapper (TM) data and the same methodology for both years – and, in finding a 4.2%/yr deforestation rate, confirmed evidence of net deforestation.

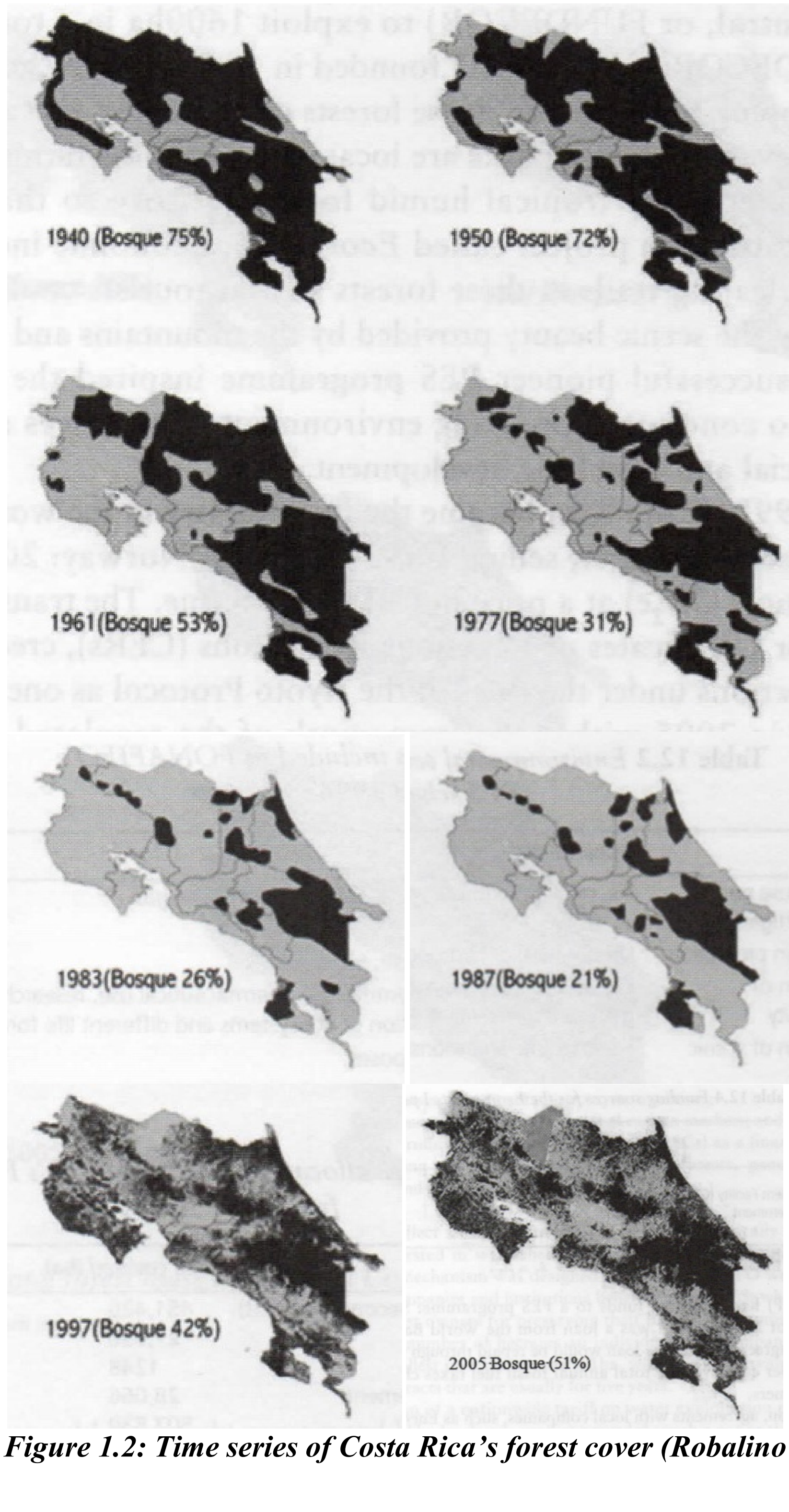

Figure 1.2: Time series of Costa Rica's forest cover (Robalino et al. 2011)

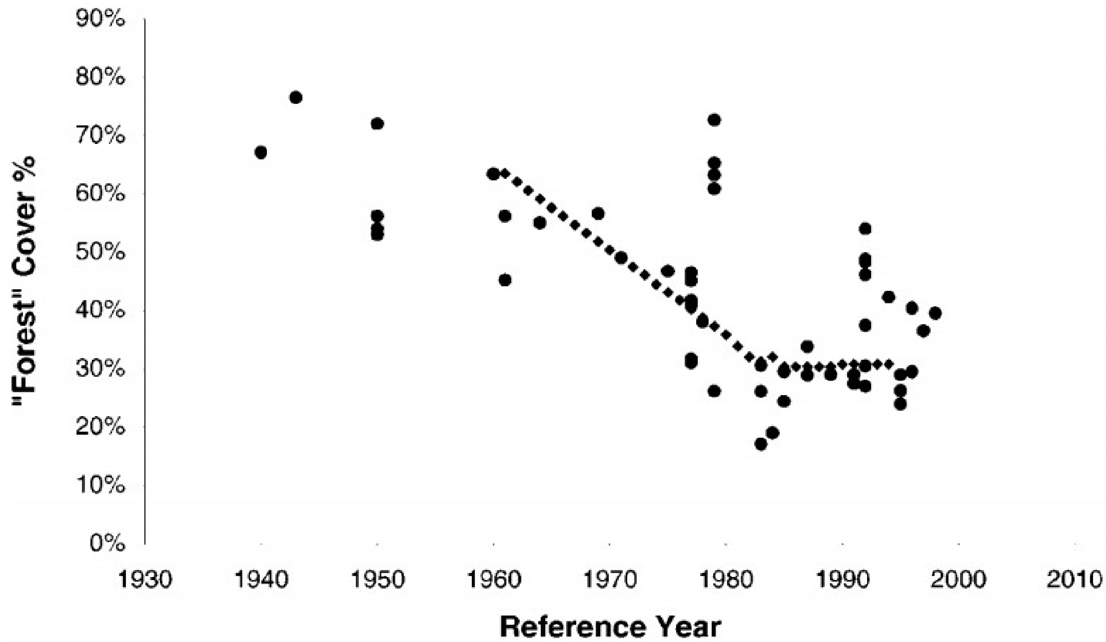

Figure 1.3: Plot of forest cover estimates for Costa Rica (Kleinn et al. 2002)

This decline in forest cover is mostly attributed to land use changes from forest to agriculture. Cash crops such as coffee, bananas, tobacco, sugarcane, and oil palm, as well as timber and cattle ranching, are among the causes. While these causes varied in prominence in different historical time periods, gradual land conversion from forest to agriculture dates back to European settlement, and was noticeably exacerbated in the 20th century by bananas, coffee, and cattle (Evans 1999). Also relevant are the development of roads (making timber extraction more viable), government policies supporting the coffee and cattle industries (in the 1950s and 1970s, respectively), and at one point even a policy (in the 1930s and 1940s, called the "denuncio" system) for obtaining property rights by clearing forest (Nygren 1995).

In response to the loss of forest, Costa Ricans began considering policy means to protect forests. Earliest efforts at forest policy predate mass awareness of forest cover loss, and date from as early as 1906 legislation calling for the executive to "recommend a general forest policy" (Evans 1999), along with other efforts such as attempts to declare "national forests" and a "national park" in the 1910s through 1940s, but they were largely unsuccessful due to a lack of meaningful enforcement (Evans 1999). Significant progress began in 1969 with the passage of a landmark *Ley Forestal* (Forest Law), No. 4465, which established a national park system that has been gradually expanded and refined over the past several decades (Evans 1999), among other things.

The system of parks and other protected areas worked well for public lands, but not private lands outside protected areas. By 1988, estimates of forested land "outside parks and reserves" ranged from 5% (based on satellite imagery) to 9% (based on aerial photography) (Evans 1999). Protecting private forest land – which is important for whole-ecosystem conservation – proved to be more difficult, due to factors like the political difficulty of imposing protection on private land and the lack of funds to outright buy land for protection. As a result, Costa Rica's policies gradually turned toward the notion of sustainable development, the general concept of integrating environmental considerations with economic activity and development.

Beginning from 1969, increasing public environmental awareness (de Camino et al. 2000) spurred the passage of a series of Forest Laws and other incentive programs in efforts to reverse the trend of deforestation. (These pre-PSA efforts are reviewed in Daniels et al. 2010, Rodricks 2010, Evans 1999, and Fonseca & Drummond, 2015.)

- Law No. 4465 (1969), which established a system of national parks on public lands, was followed by various efforts to address forest protection on private lands (Daniels et al. 2010, Rodricks 2010):
- Law No. 6184 (1977) required 2% of agricultural loans to be used for reforestation projects and capped the interest rate for such loans.
- Decree No. 10521-AH, which began in September 1979 and ended in 1985, created an income tax credit for reforestation activities (de Camino et al. 2000).
- The COREMA-AID project, which began in 1983, offered "soft credit" incentives such as low-interest loans for reforestation.

- Law No. 7032 (1986) created the Forest Payment Certificate (*Certificado de Abono Forestal*, CAF) in its Article 82. However, this law was ruled unconstitutional, which reverted forest law back to Law No. 4465.
- Decree No. 18691 MIRENEM-H (1988) created the Forest Protection Certificate (*Certificado de Abono Forestal por Adelantado*, CAFA).
- Law No. 7174 (1990), which was similar to Law No. 7032, was passed as a temporary measure, including a provision creating a commission to make a permanent revision to the 1969 law.
- Decree No. 22452-MIRENEM-H (1993) created the Forestry Payment Certificate for Forest Management (*Certificado de Abono Forestal para e Manejo del Bosque*, CAFMA), a tax voucher program for "scientifically-managed timber extraction from natural forests".
- Decree No. 23101-MIRENEM-H created (in April 1994, and implemented in 1995) the Forest Protection Certificate (*Certificado para la Protección de Bosque*, CPB), a tax voucher program for natural forest protection "equal to the CAF vouchers paid for restoration".

Leading up to 1996, there existed separate incentive programs, as shown in the list above. Some of these were funded by the World Bank, but around this time, it implemented Structural Adjustment Programmes, which eliminated these funding sources (Rodricks 2010).

Meanwhile, a National Forestry Financing Fund (*Fondo Nacional Financiamiento Forestal*, FONAFIFO) had been created in 1990 to help with financing of forestry projects (Daniels et al. 2010).

Needing new revenue sources, hoping to consolidate the incentive programs, and working with NGOs like FUNDECOR (*Fundación de Desarrollo de Cordillera Volcánica*), FONAFIFO helped develop (Karousakis 2007) a system of payments to landowners on the basis of environmental services generated by their land and paid at least in part by users of these services -- a program which became PSA as enacted under Law No. 7575.

The core of the legal framework of PSA is Law No. 7575, passed in 1996 and implemented in 1997. This law formally recognizes[1] that forests provide four services:

- mitigation of GHG emissions, via carbon fixation, sequestration, and storage
- water resource protection, via watershed protection
- biodiversity protection
- scenic beauty

Since forests provide these services, their landowners can be legally compensated for the services.

[1] *Ley Forestal* No. 7575, Article 3, section k: "Servicios ambientales: Los que brindan el bosque y las plantaciones forestales y que inciden directamente en la protección y el mejoramiento del medio ambiente. Son los siguientes: mitigación de emisiones de gases de efecto invernadero (fijación, reducción, secuestro, almacenamiento y absorción), protección del agua para uso urbano, rural o hidroeléctrico, protección de la biodiversidad para conservarla y uso sostenible, científico y farmacéutico, investigación y mejoramiento genético, protección de ecosistemas, formas de vida y belleza escénica natural para fines turísticos y científicos."

Alongside establishing a system of payments for these ecosystem services, Article 19 of *Ley Forestal* No. 7575 also banned change in soil use -- typically referred to in the literature (e.g. Fagan et al. 2013, Daniels et al. 2010) as a ban on forest clearing. This appears intended to ban all clearing of forest except through designated sustainable forest management (SFM) contracts within PSA. (However, the implementation of this contract modality might have been less than perfect (Navarro & Thiel 2007), which may have influenced its discontinuation in 2002.)

In addition to Law No. 7575, the legal framework of PSA also makes use of the Soil Conservation Law (Ley No. 7779, 1998), the Public Services and Regulatory Authority Law (Ley No. 7593, 1996), the Environment Law (Ley No. 7554, 1995), and the Biodiversity Law (Ley no. 7788, 1998) (Karousakis 2007, Robalino & Pfaff 2013).

1.4 Details of Costa Rica's PSA program

The program known as *Pago de Servicios Ambientales* (abbreviated PSA), which translates to "Payments for Environmental Services", allows for funding to be channeled through FONAFIFO into structured payments received by landowners in the form of land use contracts for various purposes, here called *modalities*, which included the following (Porras et al. 2013):

- Forest protection (areas of 2~300 ha, contract & payments for 10 years, greater payment amounts for forest protection "in conservation gaps" and "in zones of importance for water")

- Reforestation (effectively including plantations, areas of 1~300 ha, contract for 15 years, payments for 5 years, greater payments for "native species and species in danger of extinction")
- Sustainable forest management (areas of 2~300 ha, contract & payments for 10 years, discontinued 2002, briefly revived in 2011-2013) (de Camino Velozo 2015)
- Agroforestry (counted by number of trees, for 350~5,000 trees, contract for 5 years, payments for 3 years, greater payments for "native species and species in danger of extinction", begun in 2003)
- Natural regeneration (areas of 2~300 ha, contract & payments for 10 years, begun in 2003)
- Forest plantations (pilot scheme launched in 2013, via Decree No. 37660, in which "owners will not require permits to harvest plantation trees")

The vast majority of contracts, in count (67%), land coverage (90%), and contract payments (82%), have been forest protection contracts (Porras et al. 2013), although this may include some natural forest regeneration that was registered as forest protection (Daniels et al. 2010). Forest protection contracts span the geography of the country, albeit with a somewhat uneven distribution, as illustrated in Fig. 1.4, reproduced from Pfaff et al. 2008, which shows forest protection contracts from the year 2000. As reported in Porras et al. (2013), several hundred contracts are enacted every year.

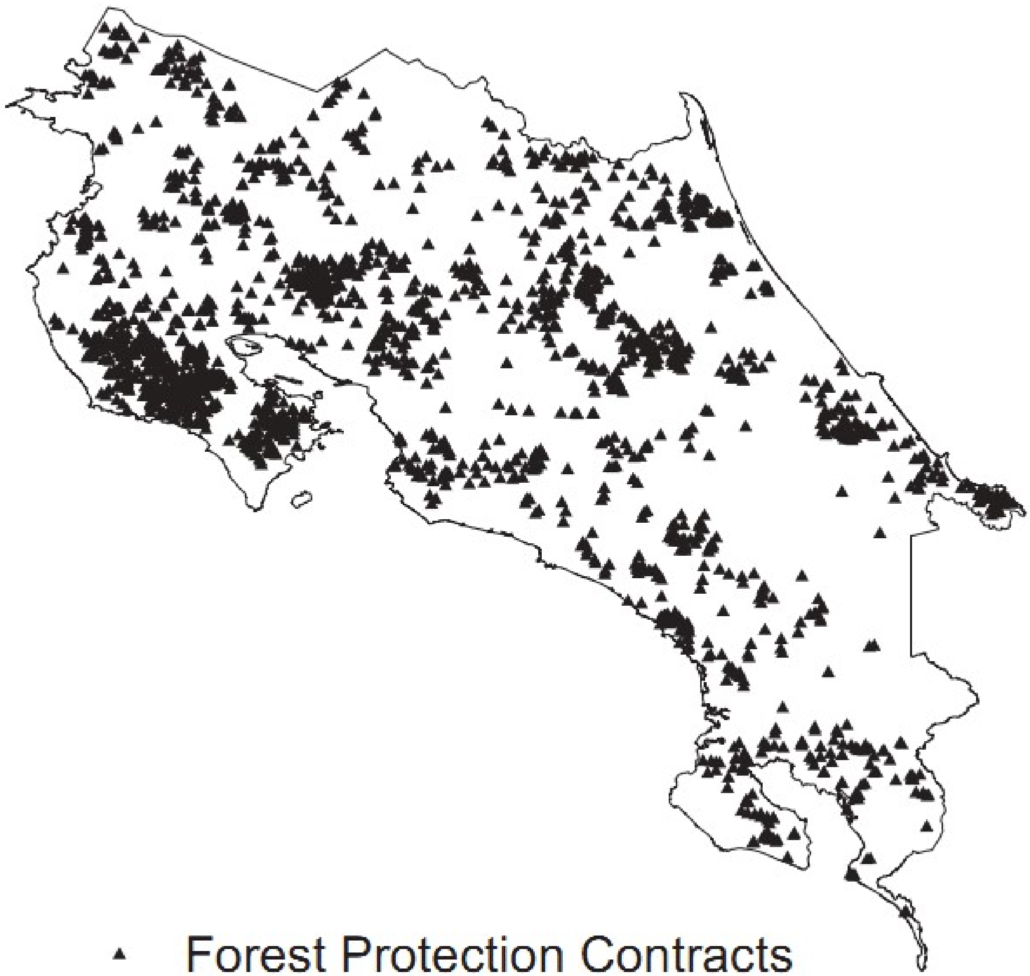

Figure 1.4: Locations of forest protection contracts in 2000 (Pfaff et al. 2008)

These yearly payment amounts vary in their structure – they may be consistent from year to year, or lopsided based on expectations of the economic use of the land, depending on the contract type. For example, forest protection contracts pay an equal amount every year while reforestation (i.e. timber plantation) contracts disburse higher sums earlier in the contract (Pagiola 2008).

PSA contracts are drawn up with the help of *regentes* (translated as licensed foresters, forest engineers, or regents, in the literature) who help draw up and certify sustainable forest management plans, which include information on "proposed land use; land tenure and physical access; topography; soils; climate; drainage; actual land use and carrying capacity with respect to land use; plans for preventing forest fires, illegal hunting, and illegal harvesting; and monitoring schedules" (Pagiola 2008).

Funding sources: PSA program funding comes from both domestic and international sources, and is roughly based on the categories of ecosystem services. They include voluntary contracts with hydrological service users (such as municipal water suppliers, hydropower utilities, bottlers, agribusinesses, and tourism establishments), a consumer tax on fossil fuels, a water tax (beginning in 2007), sales of Certifiable Tradeable Offsets (CTOs, i.e. carbon credits) on the international voluntary carbon market, and various international grants and loans (such as through the World Bank's Ecomarkets project, the REFORESTA project, and a project in Huetar Norte with the German Cooperation Bank KfW) (de Camino et al. 2000, Karousakis 2007, Pagiola 2008, and other sources).

Monitoring and enforcement: Enforcement of PSA is done via satellite imagery, site inspections, and some police monitoring of timber shipments (Navarro & Thiel 2007). Violators must return the PSA payments if the forest under forest protection contracts is found to have been cut down. However, remote monitoring may be not be able to show forest thinning practices (i.e. forest degradation).

Evolution of the PSA program: The PSA program has evolved over the years. Early in the history of the PSA program, prior subsidy prices and subsidy scheduling – from programs mentioned in the previous subsection – were "carried over" into PSA (Pagiola 2008). Some existing subsidies were even allowed to continue or were used to pay PSA payments in the early years (De Camino et al. 2000, Pagiola 2008). However, these payment details have been adjusted since, based on available budget and estimations of the value of the ecosystem services and the opportunity cost of the land (Porras et al. 2013). The program has also created new contract types and discontinued some old contract types, and has adjusted its mechanisms for targeting contracts to different landowners (see below).

Additionality/causality and program targeting: Not all land is equally valuable in generating these aforementioned environmental services. Areas such as biological corridors may be more important for biodiversity, for example. Targeting offers a way to prioritize these areas. Furthermore, targeting could allow the program to better serve -- with limited funds -- those lands on a land use economic threshold where a payment could convince the landowner to decide to reforest or against clearing forest.

Since PSA is a voluntary program, affected by potential participants' awareness of the program and their willingness to participate once they know of it, targeting is a concern in policy implementation. Sanchez-Azofeifa et al. (2007) and Robalino et al. (2011) have pointed out that the earlier years (1997-2000 and 2000-2005, respectively) of the PSA Program had relatively poor targeting efforts, while Sills et al. (2008) found a significant reduction in deforestation that could be credited to the targeting efforts of an NGO helping to implement PSA.

The following two terms are used in evaluations of this sort of environmental policy:

- *Additionality* is the idea that something would not have happened if not for the existence of the program, and thus was caused by the program. This is a common concern in international efforts to address climate change mitigation, especially with regards to forest protection, where the desired change is to avoid an action rather than to perform it – an effect that is impossible to measure directly. If the forest would have been left alone anyway, then the payment could be interpreted as "wasted" because it is not "additional" to a baseline, a counterfactual scenario wherein the program didn't exist.
- *Priority* refers to the fact that, even if all actions are additional (according to the above paragraph), not all participation produces the same amount and kinds of ecosystem services, so, given a limited amount of funds, contracts would best be given to participants whose lands can produce the most valuable services.

PSA's payment amounts already include measures to address priority, such as by offering higher payments for the use of native and/or endangered species in agroforestry and reforestation contracts (thus making biodiversity a priority). Forest protection contracts have seen the following targeting efforts:

- During the program's first year, all applicants were considered on a first-come first-served basis. (Porras et al. 2013). Demand noticeably outpaced supply of contracts (Cameron 2015).
- In 1998-2002, while FONAFIFO and the National System of Conservation Areas (*Sistema Nacional de Áreas de Conservación*, SINAC) jointly administered the program, priority categories were established for buffer areas around protected areas, indigenous lands, and biological corridors. Contracts were first-come-first-served within these categories.
- When FONAFIFO took over management in 2003, and until 2010, targeting was simplified and began to be used to prioritize the order in which applications for contracts were processed (Porras et al. 2013) and consisted of four categories (Robalino et al. 2011): (1) locations within biological corridors, (2) locations with expired contracts, (3) watershed protection areas, (4) private properties located within publicly-owned protected areas. Within these four categories, locations with low socioeconomic development (according to the Social Development Index, or Índice de Desarrollo Social (IDS), developed by the government) were given extra priority.
- Beginning in 2011, FONAFIFO again revised the priority criteria to work based on priority scoring based on factors mentioned above, as well as other factors such as property size (Porras et al. 2013).

Beyond criteria officially developed for the PSA program, some non-governmental organizations (NGOs) that facilitate PSA implementation may do targeting of their own. For example, the Foundation for the Development of the Central Volcanic Range (*Fundación para el Desarrollo de la Cordillera Volcánica Central*, FUNDECOR) "has attempted to target areas under greater threat of deforestation" (Sills et al. 2008).

The targeting criteria list lacks a measure of factors affecting the opportunity cost of land, such as distance to roads, cities, or waterways. The ability to target based on opportunity cost of land might be useful, but would be difficult to determine accurately – particularly given the simultaneous ban on clearing forest. Meanwhile, existing targeting criteria do roughly reflect environmental/social priorities. It may already be the case that these criteria implicitly impose a social value variable to the decision-making process.

CHAPTER 2: LITERATURE REVIEW

2.1 General comments

The focus of this chapter is those existing studies that aim to evaluate the effectiveness of Costa Rica's PSA program – specifically, forest protection contracts -- at preventing deforestation, and conducting this evaluation through the use of forest cover data. The basic idea involves comparing the forest cover of PSA participant properties and forest cover of non-participant properties. This first section gives a general overview of this research aim; specific studies are examined in a later section.

It is not necessarily the case that lands enrolled in PSA would be deforested if not enrolled – the problem of lack of "additionality". The PSA is a voluntary program, and it is not possible to "predict the future" to discern whether a landowner would really deforest a plot of land if not for the PSA. Therefore, estimating the effect of PSA forest protection requires estimating a "counterfactual" scenario wherein PSA does not exist.

The simplest (which can be called "raw" or "naïve") way to construct a counterfactual is to examine the activity of forested private lands that are not enrolled in the PSA. However, because PSA participation is voluntary, properties are not randomly selected for participation in PSA: therefore, PSA and non-PSA forested private properties may differ in ways that affect how much deforestation a payment can prevent, such as in their physical characteristics. This sort of "nonrandom allocation" is indeed observed, at least in 1997-2000 (Robalino & Pfaff 2013) and 2000-2005 (Robalino et al. 2008). If PSA is poorly targeted and payments are made to many lands that would otherwise have preserved forest, then the "raw" comparison may overstate the effect of the PSA. If PSA is well-targeted and payments are made to lands that are at severe risk of deforestation and prevent that deforestation, while lands at lower average risk of deforestation are uncontracted by PSA, then this "raw" comparison may understate the effect of the PSA.

Because of the possibility of nonrandom allocation, some studies use statistical techniques from the field of econometrics to control for impact of other factors, in order to get a more accurate assessment of PSA's effectiveness. A basic technique in econometrics is ordinary least squares (OLS), which assumes a relationship between the dependent variable (forest cover or deforestation amount) and some number of potentially confounding factors (such as distances to roads, cities, and ports) as well as the independent variable (whether the property is enrolled in PSA). PSA-enrolled and not-PSA-enrolled properties are entered into a regression equation to determine the relationship numerically. Quasi-experimental studies go further by using matching methods to screen non-enrolled locations for ones that are (according to some number of measures) most similar to enrolled locations. The measures for this similarity, called “covariates”, often include a variety of both geographic and non-geographic features, such as distance to nearest city/school/sawmill/city/river, province/canton/district, elevation, slope, precipitation, Holdridge Life Zone, and property owner characteristics (e.g. residence on/off property, education level, income level) (Porras et al. 2013). The number of matches used, whether matches must be unique to each PSA-enrolled location, and the choice to use a "caliper" to ensure that matches cannot be too different from each PSA-enrolled location, can be decided by the researchers, as well as the choice between two different matching methods:

- *Propensity score matching* (PSM), developed by Rosenbaum & Rubin (1983), which interprets the covariates as affecting the probability of enrollment, and
- *Nearest-neighbor covariate matching* (CVM), developed by Abadie & Imbens (2006), which considers covariates as a multidimensional space and selects those non-PSA locations "closest" to PSA locations in that space.

This comparison method focuses specifically on the effect of the PSA payment vs. non-participation in PSA. Even so, it may not be able to “peel off” some effects, the most notable of which is the concurrent ban (from the same law) that essentially prohibits clearing of forest. Furthermore, PSA can incentivize (and educate landowners about) responsible and active methods of forest management. In addition, before and during the time in which the PSA has been implemented, there have been various changes to the economy – a fall in beef commodity prices (combined with decreased government subsidies for the cattle industry) and a rise in ecotourism may have contributed to the trend of falling deforestation and more forest protection. PSA may even have further secondary effects, such as encouraging gradual urbanization of the country via abandonment of agriculture (Legrand et al. 2011). For the purpose of evaluating the impact of PSA, as well as concluding how much Costa Rica's experience with PES is applicable to other countries, these caveats must be taken into account.

Meanwhile, forest protection PSA contracts are assumed to be well-enforced and thus its deforestation rate is assumed to be zero. Robalino et al. (2015) comments that this is "an essentially correct assumption", and that despite this there may be "within-property leakage effects" that result in deforestation, because contract area is not necessarily the same as property size.

Finally, data must be collected or sourced from existing datasets. For non-PSA properties, forest cover can be measured by various means, including in-person fieldwork, aerial photography, and satellite imagery. There are several existing forest cover datasets for the country, produced by collaborations of the Center for Earth Observation Studies (CEOS) at the University of Alberta, the Tropical Science Center (*Centro Científico Tropical*, CCT), the Ministry of the Environment (*Ministerio de Ambiente y Energía*, MINAE), and FONAFIFO. These exist for the years 1997, 2000, 2005, 2010, and 2013, and are based on Landsat and SPOT imagery. (EOSL & CCT 2002, FONAFIFO 2007, and FONAFIFO 2012 are the forest cover reports for all of these except 2013.) Some researchers have used these land cover studies, while some researchers have used their own imagery (such as aerial photography) and/or taken additional steps to interview landowners about their land use, environmental awareness, and other information. Data on demographics, economic factors, and landowner knowledge/opinions/intentions can be obtained through surveys and interviews, as well as Costa Rican census data.

2.2 Studies evaluating the impact of Costa Rica's PSA program on deforestation and forest cover

A number of studies have been done attempting to evaluate the effectiveness of Costa Rica's PSA in preventing deforestation. Some studies cover the entire country while others cover only a portion. They also cover different periods of time. A selection of these studies are summarized in Table 2.1, which shows them and their attributes in chronological order of publication, and are described in the text synopses below, which are sorted based on their geographic range and whether they were published in a peer-reviewed journal (indicated by italics in Table 2.1).

Table 2.1: Selected studies of Costa Rica's PSA program

Authors	**Year**	**Publication *(italics = peer-reviewed publication)***	**Geographic area**	**Reference years**	**PSA mode(s)**	**Statistical method(s)**	**Forest cover data**	**Fieldwork**
Sierra & Russman	**2006**	*Ecological Economics*	Osa Peninsula	2003	Protection	OLS	CEDARENA, MINAE	Interviews
Sánchez-Azofeifa et al.	**2007**	*Conservation Biology*	Whole country	1986-1997 vs. 1997-2000	All	OLS	1986, 1997, 2000 Landsat-based forest cover maps (U. Alberta)	
Pfaff et al.	**2008**	Sanford Institute Working Paper Series	Whole country	1986-1997 vs. 1997-2000	Protection	"Naïve", PSM, CVM	Landsat-based forest cover maps (U. Alberta)	
Robalino et al.	**2008**	Environment for Development Discussion Paper Series	Whole country	2000-2005	Protection	CVM, PSM	2000/2005 forest cover maps, probably from U. Alberta	None
Sills et al.	**2008**	World Bank PES Learning Paper (intended for Platais & Pagiola book)	Sarapiquí region	1997-1999	Protection(?)	Prematching, PSM	1992 & 2005 aerial photos (ITCR)	Interviews and survey
Calvo-Alvarado et al.	**2009**	*Forest Ecology & Mgmt.*	Guanacaste	1960-2005	Protection, Management	Not directly evaluated	Aerial photography, Landsat	None
Morse et al.	**2009**	*Ecology & Society*	San Juan-La Selva area	1986-1996 vs. 1997-2001	All		1986, 1996-1997, 2001 Landsat 5 images (authors' own classification work)	Household surveys, field validation
Arriagada et al.	**2011**	2011 BioEcon Conference	Whole country, rural areas only	Contracts signed 1998-2004	Forest protection	PSM using census tracts	U. of Alberta data	
Robalino et al.	**2011**	Rapidel et al. book	Whole country	2000-2002 vs. 2003-2005	Forest protection	PSM	2000, 2005 forest cover maps (U. Alberta)	
Arriagada et al.	**2012**	*Land Economics*	Sarapiquí region	1997-2005	Protection	Prematching	1986, 1992, 2005 aerial photos & Landsat 5	Surveys
Fagan et al.	**2013**	*Environmental Research Letters*	San Juan-La Selva area	1986-2011	Deforestation ban	Forest cover/type time series	Landsat images	Field validation data
Robalino & Pfaff	**2013**	*Land Economics*	Whole country	1997-2000 (1997, 1998, 1999 contracts)	Forest protection	"Naïve", OLS, PSM	1986, 1997, 2000 forest cover maps (U. Alberta)	
Robalino et al.	**2015**	*PLoS ONE*	Whole country	2000-2005	Forest protection	PSM	2000, 2005 forest cover maps	None

2.2.1 Whole-country studies, peer-reviewed papers

Robalino et al. (2015) - "Evaluating Interactions of Forest Conversation Policies on Avoided Deforestation"

This paper explores the interaction between the PSA and the national park system (i.e. protected areas), between 2000 and 2005, and finds that, while PSA, parks, and buffers around parks have an impact on reducing deforestation, combining parks and PSA does not increase the impact, nor does adding PSA to areas in buffer zones around parks. Spatial data was "public data" from which they selected 50,000 random points and picked relevant ones (14,510 used in total), a technique used in other papers from the same authors, suggesting that they used the same dataset. Non-PSA locations were matched to PSA locations using propensity score matching.

Robalino & Pfaff (2013) - "Ecopayments and deforestation in Costa Rica: a nationwide analysis of PSA's initial years"

This paper is similar to Pfaff et al. (2008), which was not published in a peer-reviewed journal. But instead of drawing from 10,000 randomly selected points, this paper draws from 50,000 randomly selected points; the covariates used are also slightly different, and this paper uses different numbers of matches and occasionally a caliper for matching. Both propensity-score and nearest-neighbor covariate matching are still used. The same data source is used for forest cover data. The results estimated deforestation rate at 0.20%, and further analysis found that PSA prevented 0.11% or less of that – in other words, from 1997-2000, "estimates of PSA impact do not differ significantly from zero".

Sánchez-Azofeifa et al. (2007) - "Costa Rica's payment for environmental services program: intention, implementation, and impact"

This study performed a spatial analysis of the PSA program, using a set of forest cover maps for 1986, 1997, and 2000 (which the lead author's organization produced for FONAFIFO), along with GIS maps of hydrological, ecological, and other features, and a map of PSA contract areas. They found “very low”overall annual deforestation rates to be 0.06% for 1986-1997 and 0.03% in 1997-2000, and their OLS analysis relating deforestation rate to PSA density concluded that PSA during this period "did not reduce deforestation rates".

2.2.2 Whole-country studies, non-peer-reviewed papers

Robalino et al. (2011) - "Assessing the Impact of Institutional Design of Payments for Environmental Services: the Costa Rican Experience"

This study uses matching techniques and covers the period 2000-2005. Starting with 50,000 random points, excluded inapplicable points (e.g. points with uncertain forest cover, points not forest in 2000, points in protected areas and government lands), and compared them to PSA contracts. It also subdivided the period into 2000-2002 and 2002-2005, because the PSA program was managed by SINAC during the former and FONAFIFO during the latter. It found that forest protection contracts had an estimate avoided deforestation of 0.50% by raw comparisons, and this estimate improved to

0.61% for SINAC and 0.67% to 069% for FONAFIFO, after matching techniques were applied. (It is unclear whether this paper was peer-reviewed.)

Arriagada et al. (2011) - "Payments for environmental services and their impact on forest transition in Costa Rica"

This study covers the period 1997-2005 (using PSA contracts from 1998-2004), and uses 8214 rural census tracts rather than randomly selected points as units of analysis, in order to gather demographic data, for the purpose of doing propensity-score matching. Forest cover data from the University of Alberta datasets were used, like in several other studies mentioned here. It concludes that the program had little additional effect in protecting existing forest but did have a statistically significant effect on establishing new forest: "between 1.1% to 1.17% of the average size of PSA tracts, 2.7% and 4.4% of the average forest cover in 1997 in PSA tracts, and 7.3% and 11.6% of the average land enrolled in PSA."

Pfaff et al. (2008) - "Payments for Environmental Services: Empirical Analysis for Costa Rica"

This uses spatial data on forest cover (from 1986, 1997, and 2000) and PSA contract data (from 1997, 1998, and 1999) to compare PSA with non-PSA parcels. Non-PSA parcels are selected from 10,000 randomly-chosen points, then excluding inapplicable points such as public lands and cloud cover. Matching is done using auxiliary spatial data about land characteristics -- both propensity score matching and nearest-neighbor covariate matching; the authors test different numbers of matches (one was insufficient). They find an annual deforestation rate of 0.21% for non-PSA land, but with matching, PSA only seems to prevent 0.08% of that per year.

Robalino et al. (2008) - "Deforestation Impacts of Environmental Services Payments: Costa Rica's PSA Program 2000-2005"

This paper follows Pfaff et al. (2008) (labeled as "Pfaff et al. 2007" in the paper), and largely applies the same method as that paper, but to the period 2000-2005. Using forest cover maps from 2000 and 2005, and a slightly different set of matching variables, but again doing both propensity-score and nearest-neighbor covariate matchng. This paper draws 50,000 random points, rather than 10,000 which its predecessor does. Forest cover data source is not specified but presumably the same as the above. They find an annual deforestation rate of 0.28% for non-PSA land, but for land that is specifically similar to PSA lands, that rate is higher, with estimates ranging from 0.33% to 0.46%, implying that PSA targeting was having a proper effect.

2.2.3 Regional studies, peer-reviewed papers

Fagan et al. (2013) – "Land cover dynamics following a deforestation ban in northern Costa Rica"

This study focuses on the 1996 Forest Law as a "deforestation ban", rather than the PSA program itself. Using a time series of five Landsat images and field validation data, it mapped the forest cover and forest types as well as cropland during the period 1986-2011, and it used those maps to compare deforestation rates before and after the ban, in the northern lowlands of the country, around San Juan La Selva Biological Corridor. It found that mature forest loss was reduced from about 2.20%/yr to about 1.38%/yr, while total forest cover remained "relatively constant" as agriculture shifted to occupy lands that were formerly exotic tree plantations, while native reforestation has fluctuated.

Arriagada et al. (2012) – "Do Payments for Environmental Services Affect Forest Cover? A Farm-Level Evaluation from Costa Rica"

A study in the Sarapiquí area (northeastern Costa Rica), performed with interviews and surveys of landowners of PSA and non-PSA properties, as well as using aerial photos and (supplementarily) Landsat 5 to determine farm-level land cover change from 1992 to 2005. Using matching techniques, this study estimated the impact on the average farm of about 8.5 to 12.7 ha of forest difference, turning expected forest loss of about 1.35 ha in a counterfactual scenario without PSA into a gain of about 12.74 ha, on average.

Morse et al. (2009) – "Consequences of Environmental Service Payments for Forest Retention and Recruitment in a Costa Rican Biological Corridor"

A study of forest retention, recruitment, and connectivity, in the San Juan La Selva area in northern Costa Rica. The authors created their own classifications of Landsat 5 images from 1986, 1996-1997, and 2001, and they used a counterfactual estimate made from landowner surveys to model prevented deforestation. They estimated that PSA prevented 1.04% of deforestation, if there were no ban on forest clearing.

Calvo-Alvarado et al. (2009) – "Deforestation and forest restoration in Guanacaste, Costa Rica: Putting conservation policies in context"

This study focused on a long-term analysis of social dynamics that led to deforestation and forest recovery in Guanacaste over the period of 1960-2005. It mentions PSA as part of a set of national conservation policies influencing the region, but notes that the PSA program is too recent as of the end of this study for it to be particularly relevant to explaining forest recovery. Also, this study used Landsat MSS imagery and classified 80% forest canopy cover as forest.

Sierra & Russman (2006) – "On the efficiency of environmental service payments: A forest conservation assessment in the Osa Peninsula, Costa Rica"
A study of farms in the Osa Peninsula in southern Costa Rica. This study focused on land-use decisions in PSA protection farms vs. non-PSA properties, using ordinary least squares to discern the effect of PSA. The study found that having a PSA contract accelerates transition toward non-agricultural land use, though even in non-PSA farms forest regrowth would still be expected, "albeit at a slower rate."

2.2.4 Regional study, non-peer-reviewed paper

Sills et al. (2008) - "Impact of the PSA Program on Land Use"
This study aimed to use quantitative surveys and qualitative interviews, as well as aerial imagery, to determine the casual impact of PSA on forest cover in the Sarapiquí region in 1997-1999. Forest cover data was drawn from 1992 and 2005 aerial photographs from the *Atlas Digital de Costa Rica 2004*, which also supplied auxiliary data. It concludes that PSA reduced deforestation by about 10% in this region, though not in the entire

country, likely because of effective targeting by the Foundation for the Development of the Central Volcanic Range (*Fundación para el Desarrollo de la Cordillera Volcánica Central*, FUNDECOR). While not directly specified, the PSA modality studied appears to be protection.

In addition to papers evaluating the forest protection benefits of PSA, there are others that evaluate different modalities (such as Cole 2010, which examines agroforestry contracts) or focus instead on participation in and socioeconomic impacts of PSA (e.g. Zbinden & Lee 2005, Arriagada et al. 2009, Arriagada et al. 2015).

2.3 Discussion

A common methodology shared by a few studies (which also share some authors) is the approach of selecting 50,000 random points, excluding irrelevant points, and measuring deforestation rate on them using remotely-sensed data, such as via existing forest cover maps for the country. This has been done for the time periods 1997-2000 (Robalino & Pfaff 2013, Pfaff et al. 2008) as well as 2000-2005 (Robalino et al. 2011, Robalino et al. 2008), and results generally bear out the observation that (1) there is little deforestation in Costa Rica (less than 1%), and (2) PSA in 1997-2000 had less of an effect than PSA in 2000-2005. This makes sense given PSA priority criteria were refined in 1998 and then later in 2003. Meanwhile, results from a variety of regional studies have shown various results, often greater than 1%, possibly as high as 10% (Sills et al.

2008). This may be due to local efforts to target PSA, as well as ability to evaluate a larger variety of covariates because interviewing landowners and understanding the socioeconomic attributes of land parcels is more feasible in localized studies.

These studies also show a variety of research foci. Robalino & Pfaff (2013) and Robalino et al. (2008) are both whole-country studies using spatial data on PSA and on forest cover, with no supplemental interviews, and both use matching methods to go beyond "naïve" and ordinary-least-squares comparisons to try to remove compounding variables. Meanwhile, Arriagada et al. (2011) evaluates PSA with the framing of "forest transition" (a shift in a developing country from losing forest to regaining forest), rather than forest protection directly, and finds "no statistically significant effect on existing forest" but "a statistically significant and positive effect on the establishment of new forest". And Fagan et al. (2013) is the only one of these studies that focuses on the "deforestation ban" (i.e. ban on soil use change), though PSA and the ban are essentially concurrent. There are also different choices of units of analysis – the random point, the individual property, and the census tract; these lead to different means for obtaining information about the economic conditions of a given location.

CHAPTER 3: ESTIMATING DEFORESTATION RATE OUTSIDE PSA CONTRACTS

3.1 Introduction

In order to evaluate the effectiveness and impact (specifically on deforestation prevention) of PSA, this dissertation examines two major aspects, in the following three ways:

- Estimating the deforestation rate outside of PSA contracts. (this chapter)
- Examining whether deforestation has occurred inside PSA contracts. (Chapter 4)
- Geographically focused case studies for demonstration, verifying the information found in chapters 3 and 4. (Chapter 5)

The goal of the analysis covered in this chapter was to estimate the rate of deforestation for forested land outside of PSA contracts. However, not all land is forested, and not all forested land makes a reasonable comparison – protected areas, for example, are protected for reasons other than PSA payments. Therefore, the overall procedure was to sample areas that fit certain criteria for relevance, and find the deforestation rate over time in those areas.

3.2 Data sources

3.2.1 List of data sources

Data for the analyses in this dissertation came from the following sources. (This section includes datasets not directly pertinent to this chapter, and will be referred to by other chapters.)

PSA contract locations, including contract types, were acquired from FONAFIFO. PSA contracts are given in polygon or point shapefiles. These shapefiles cover the years 2011-2019, one per year, and each shapefile shows the location, type, and spatial coverage or number of trees (the latter for agroforestry contracts) for all contracts finalized that year. Two sets of shapefiles were acquired:

- The first set (hereafter called FONAFIFO 2018) consists of polygon shapefiles for all years 2011-2018, bears timestamps in 2018 (2018-05-11 for all contract years except 2018; 2018-09-28 for contract year 2018), and was acquired from FONAFIFO in early 2019.
- The second set (hereafter called FONAFIFO 2020) consists of the shapefiles as the first set for 2011-2014, but instead has point shapefiles for years 2015-2019, with timestamps 2020-02-27 for all contract years except 2019; 2020-05-27 for contract year 2019, and was acquired from FONAFIFO in September 2020. (This second set also includes kml files,

which can be opened in Google Earth; they also consist only of points, not polygons.)

Table 3.1 contains summary statistics of these two datasets, and compares them to the number of contracts listed in several of the documents on FONAFIFO's *Estadísticas de PSA* page (timestamped 2020-05-07; FONAFIFO 2020a). Both FONAFIFO 2018 and FONAFIFO 2020 contain the same number of contracts in 2011-2014, slightly lower than the count in the *Estadísticas*, while the two datasets differ in 2015-2018 contracts, with FONAFIFO 2018 showing a far lower number of 2018 contracts. FONAFIFO 2018 may thus be an incomplete database of contracts for those years. The *Estadísticas* quantity of 732 contracts in 2019 has a comment appended indicating that the quantity of contracts may change in the process of formalization; the same likely applies to FONAFIFO 2018.

Table 3.1: Summary statistics of FONAFIFO datasets on PSA

	2010	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*
FONAFIFO 2018 contract count	*(no data)*	1201	1229	1159	938	1020	768	626	202	*(no data)*
FONAFIFO 2018 timestamps		2018-05-11							2018-09-28	*(no data)*
FONAFIFO 2020 contract count	*(no data)*	1201	1229	1159	938	1025	782	627	665	732
FONAFIFO 2020 timestamps		2018-05-11				2020-02-27				2020-05-27
FONAFIFO *Estadísticas* 2020-05-07	1120	1224	1238	1248	947	1024	783	623	666	732

Even though FONAFIFO 2018 appears incomplete, the fact that it is in polygon shapefile format remains more useful for the analysis in this dissertation, because this requires identifying the geographic extent of PSA contracts, such as for excluding randomly-sampled points which fall in PSA contract areas (section 3.3) or assessing forest cover/loss raster pixels in their geographic coverage (section 4.3).

Forest cover/loss data were acquired as follows:

- Forest cover data for 1997, 2000, 2003-2005, 2009-2010, and 2013 were acquired from the University of Alberta Centre for Earth Observation Sciences (CEOS). This research center has worked with FONAFIFO several times in developing forest cover maps for the country. Reports accompanying these forest cover maps were obtained from CEOS/FONAFIFO, for all years except 2013 (1997-2000: U. Alberta & CCT 2002; 2003-2005: Sánchez-Azofeifa et al. 2007; 2009-2010: FONAFIFO 2012), indicating that the data for the first few studies were derived from interpretation of Landsat imagery (from Landsat 5's Thematic Mapper (TM) and Landsat 7's Enhanced Thematic Mapper Plus (ETM+) sensors), and (owing to the failure of the scan-line corrector on the ETM+) SPOT 2, 4, and 5 images were used for the 2010 dataset. However, these data eventually went unused, due to geographic misalignment resulting from my inability to convert from its datum/coordinate system to the rest of the datasets used; see note after this list for explanation).

- Forest cover data for 2010 were acquired from the Global Land Analysis & Discovery (GLAD) research group at the University of Maryland (UMD), specifically the "Global 2010 Tree Cover (30 m)" dataset, which provides "per pixel estimates of circa 2010 percent maximum (peak of growing season) tree canopy cover derived from cloud-free annual growing season composite Landsat 7 ETM+ data", supplemented by other methods (Hansen et al. 2013, accessed at https://glad.umd.edu/dataset/global-2010-tree-cover-30-m). The result is an estimated maximum percentage tree canopy cover, in whole numbers from 0 to 100, in a raster format. This global dataset is divided into 10x10 degree "granules" (square regions) spanning most of the globe, and specifically the data used here came from the two granules whose top left corners are 10°N 90°W and 20°N 90°W (together they cover the full extent of the country, including the remote Cocos Island National Park). (This will hereafter be referred to as the "GLAD 30m data".)
- Forest loss data were acquired from the "Global Forest Change 2000-2019" dataset, also produced by GLAD at UMD (Hansen et al. 2013, credited as Hansen/UMD/Google/USGS/NASA). Data for the same two granules (as described above) were acquired; it is also in raster format, with the same spatial resolution. This source provides several datasets, of which the most relevant is year of gross forest cover loss event (hereafter referred to as "loss year"), coded as 1 to 19, representing the year (from

2001 to 2019, respectively) in which forest was lost in that pixel. If forest was not lost in any of these years, the pixel was assigned the value 0.

Ancillary data were acquired from FONAFIFO as well as the National Institute of Statistics and Census (*Instituto Nacional de Estadistica y Censos*, abbreviated INEC), a Costa Rican government agency. FONAFIFO data (updated as of 2020-02-29, though their individual timestamps make this unclear) included protected wilderness areas, indigenous territories, areas of conservation importance, biological corridors, hydrological resources, and social development index. INEC data included locations of airports (2018), conservation areas (which are administrative, not to be confused with protected areas), protected areas (2011), sawmills (2014), cities (2011), slope (no timestamp available), mean annual precipitation (2014), primary/secondary/tertiary roads (2014), and political subdivisions of the country (provinces (2011), cantons (2018), and districts (2011)), which were used to make a country mask for viewing convenience.

3.2.2 Comments on data sources

The various datasets used a few different datums/coordinate systems: data from FONAFIFO uses Costa Rica Transverse Mercator 2005 (CRTM05), which has its own datum (CR05); since this is the most critical data, and since ArcGIS has the ability to convert from it to other standard spheroids, CRTM05 was chosen as the standard coordinate system for the analysis here. INEC data use a coordinate system identified as "Transverse_Mercator", whose projection is the same as CRTM05, but whose spheroid is

GRS 80 (instead of CRTM05's WGS 1984). CEOS data, on the other hand, use a coordinate system identified as "165_Lambert_Conformal_Conic", whose projection is nearly identical to the "Costa Rica Lambert Norte" projection (a.k.a. "Costa Rica Norte", an older projection centered on the northern part of the country, but used by CEOS data for the entire country), but with the WGS 1960 spheroid instead of the Clarke 1866 spheroid (which is used in Costa Rica Lambert Norte). Unfortunately, I did not have a way to convert this coordinate system to properly align CEOS data with other data available, but a 2010-2013 analysis was performed anyway and is described in Appendix A. A comparison of data alignment is also shown in Appendix A.

The combination of forest loss data (specifically) and forest cover data from 2010 means that the amount of forest in 2010 can be used as a "baseline" with gross forest loss happening in subsequent years. However, this locks us into using 2010 as a standard of comparison ("where was forest lost, compared to what was forest in 2010?"). Fortunately, PSA and forest loss year data are available starting in 2011, averting a large time gap.

Also, forest cover data is not directly available, but must be derived from tree canopy cover percentage. Due to the procedures used below, a binary distinction of forest vs. non-forest was needed, so the threshold was set at 50% (50% and below = non-forest, 51% and above = forest). This is consistent with how Hansen et al. (2013) use it in their own paper (see their supplementary materials). However, it should be noted that (1) "forest" is not a binary designation in real life (but instead may be subject to degradation/thinning), (2) forest is not equivalent to canopy cover, especially in conservation efforts, but instead involves various ecological considerations (e.g. edge vs. interior forest), while canopy cover can be increased by certain anthropogenic land uses that nevertheless change the ecosystem, and (3) a different canopy cover percentage threshold is in use in some contexts (Wunder (2003) discusses this further, specifically with regards to the United Nations Food and Agriculture Organization's (FAO) definition, whose crown cover threshold is 10%, among other criteria). Thus, the 50% threshold should be seen as a procedural convenience rather than an authoritative designation.

Pixels indicated in loss years 2011, 2012 and 2013 were checked to see whether they actually lined up with forested locations in 2010 based on the GLAD 30m data with the >50% threshold. These datasets were converted into polygon shapefiles, and the GLAD 30m data was reclassified based on the threshold then its forest portions were extracted into their own shapefile (see section 3.3 for details of procedure). Of 147204 polygons (some outside Costa Rica) in the combined 2011-2013 loss year map, 23639 polygons did not intersect any forested polygons. That said, the following analysis avoided the problem of using locations where forest was lost without being present beforehand, by preselecting random points only in areas where forest was present in 2010.

3.3 Data analysis procedure

The following procedure was used in ArcGIS 10.4 to perform this analysis.

First, 50000 random points were generated within the extent of the country, using the Create Random Points tool. (As previously described, a province map from INEC was dissolved to create a country mask, for use with this tool.) The choice of this number random points was based on the work of Robalino et al. (2008), which generated this same number of random points to cover the entire country, in their econometric analysis of PSA impacts.

Second, random points that did not fall within forest – which was defined as pixels with >50% tree canopy cover in GLAD 30m data – were excluded. This raster dataset had to be adapted to a polygon first, as ArcGIS seems unable to select features (e.g. points) based on attributes in a raster. However, polygon shapefiles are not well-suited for representing raster data, and have far larger filesizes, while the shapefile format cannot contain more than 2 GB of data. Therefore, the following procedure was used to keep the dataset to a manageable size:

- Mosaic the two granules' rasters together (or work with them separately; either way works).
- Reclassify the raster data as forest/non-forest, based on the 50% criterion. (If this step is not performed before the format conversion, a raster to polygon conversion for even just the northern granule will exceed the shapefile size limit.)
- Clip (using the Clip tool in the Raster toolset) only the portion of the mosaicked raster corresponding to the area of Costa Rica – or rather, for the sake of not missing data, create a new polygon shapefile outlining a

border slightly larger than Costa Rica, and use that as the mask for clipping the combined raster.

- Convert this masked raster to a polygon, using the Raster to Polygon tool in the Conversion toolbox. Choose not to simplify polygons, because doing so would smooth the pixelated features of the raster, potentially introducing new error.

At this point, there existed a polygon shapefile of an area slightly larger than the country, containing forest/non-forest data for 2010 according to GLAD's 30m tree cover data. From this, another polygon shapefile was created that contained only forest areas, because ArcGIS doesn't directly allow selecting from the random points based on attributes in a combined forest/non-forest shapefile. Then, all random points that intersected with forested areas were selected and all other points were excluded. 34499 points remained.

Third, points that were in protected areas were excluded, because the point of this analysis is to evaluate the effect of PSA on forest protection, and protected areas are under the protection of different mechanism. FONAFIFO's shapefile of protected areas was used to determine this. The shapefile has a 2020 timestamp, so it was assumed that no protected areas had become degazetted, so that the greatest possible extent of protected areas were excluded. 22980 points remained.

Fourth, points that were already in PSA contracts (of any type, not just forest protection) were excluded. The temporal extent of the analysis is determined by this step, and this was repeated for six different time ranges, spanning one more year at a time from

2010-2013 to 2010-2018. This procedure requires using polygon shapefiles, meaning that only the FONAFIFO 2018 dataset's polygon shapefiles were usable. However, for years 2015-2018, this dataset seems incomplete, so analysis beyond 2014 may introduce additional inaccuracies.

Table 3.2 shows the points that remained after successively excluding the geographic extent of each year of contracts (as given in FONAFIFO 2018); different exclusions were used depending on the year for the estimate.

Table 3.2: Count of randomly-selected points remaining after PSA exclusions

After excluding contracts from…	2011	2012	2013	2014	2015	2016	2017	2018
…this many points remained:	22185	21545	20993	20615	20128	19974	19737	19640

(Attempting to excluding points in 2017 via the usual "Select By Location" dialog box caused ArcMap to crash unavoidably; the Intersect tool in the Analysis toolbox was needed to proceed.)

Finally, all remaining points were checked against the Global Forest Change forest loss year data for all years beyond 2010 up to the extent of the analysis period (e.g. 2011-2013 loss year data, for the 2010-2013 analysis). As mentioned before, loss year data was in raster format, and had to be converted to polygon format (again without smoothing, to minimize the potential for new error). The number of points (which were forest in 2010 and not in any protected areas or PSA contract areas) at which forest was lost in subsequent years in the analysis period was determined. This quantity was divided by the total number of points remaining in the analysis at that stage, to calculate overall deforestation rate over that entire time period. These figures were also entered into Equation 3.1, in order to estimate average annual deforestation rate as an arithmetic mean (linear) forest loss amount per fixed total amount of forest.

Equation 3.1: Forest cover as a linear function of deforestation rate

$$F_f = F_0\,(1 - rt)$$

where

F_f = Number of points with forest cover after a given time period.

F_0 = Total number of points remaining at the beginning of that period.

r = Average annual deforestation rate, to be reported as a percentage, to three significant figures.

t = Duration of that time period, in years (here, a whole number equal to the number of years since 2010).

The point count reported is the number of deforested points, which is simply related to the number of forested points as shown in Equation 3.2.

Equation 3.2: Total forest cover

$$F_f + F_d = F_0$$

where

F_d = Number of points intersecting with loss year polygons.

Rearranging and combining these equations, we can solve for r as in Equation 3.3.

Equation 3.3: Linear deforestation rate as a function of forest cover

$$r = \frac{F_d}{F_0 t} = \frac{F_0 - F_f}{F_0 t}$$

A different calculation could have been performed using the percent change formula to produce a geometrically averaged (i.e. this amount of percent reduction in forest cover year on year would produce the given result) deforestation rate, using Equations 3.4 and 3.5.

Equation 3.4: Forest cover as a function of percent change deforestation rate

$$F_f = F_0\,(1 - r)^t$$

Equation 3.5: Percent change deforestation rate as a function of forest cover

$$r = 1 - \left(\frac{F_0 - F_d}{F_0}\right)^{\frac{1}{t}} = 1 - \left(\frac{F_f}{F_0}\right)^{\frac{1}{t}}$$

However, this might overestimate deforestation rate because the data available account only for gross deforestation, not net deforestation (this second method tries to account for a decreasing reference amount of forest), and thus may result in a higher estimate for deforestation rate. Therefore, the decision was made to use the linear calculation.

As mentioned above, this procedure was carried out with step four repeated for multiple timeframes. Some of these timeframes may be particularly meaningful with regards to data quality, as follows:

- 2010-2013, because this was the original temporal extent of interest from working with the CEOS dataset (as detailed in Appendix A).
- 2010-2014, because this is the extent to which the FONAFIFO 2018 and FONAFIFO 2020 datasets are identical and in polygon format (avoiding potential issues with incomplete PSA data in subsequent years).
- 2010-2017, because this is the extent to which FONAFIFO 2018 and FONAFIFO 2020 datasets agree or approximately agree on the number of contracts finalized; PSA data for 2015-2017 is only in polygon format from FONAFIFO 2018 however.
- 2010-2018, because this is the furthest temporal extent of PSA data available in polygon format, even though data quality is expected to suffer due to incomplete PSA data in 2018.

3.4 Results

Table 3.3 summarizes the results of these calculations performed according to the procedure in section 3.3 (with linear deforestation rate calculation). Figures 3.1, 3.2, 3.3, 3.4, 3.5, and 3.6 illustrate the geographic distribution of these points with forest loss, among all points randomly selected that were neither in protected areas nor in PSA contracts during those years – for example, Fig. 3.1 highlights (in a dull orange color) those points that were forested in 2010 (according to GLAD 30m data with a >50% threshold for classification as forest cover), were not in protected areas, were not in PSA contracts in 2011-2013, and had forest loss during 2011-2013. Analogous maps for the periods ending in 2014, 2015, 2016, 2017, and 2018 are shown in subsequent images; forest loss year is roughly color-coded according to the color scheme used in Fig. 4.7. The most extensive temporal coverage that is uses reasonably accurate data (see the discussion earlier and Table 3.1) gives an estimate of 0.379% over the period 2010-2017; the 2010-2015 figure of 0.309% will be used in Chapters 4 and 5 for comparisons.

Table 3.3: Deforestation rate estimates for 2010-2013 to 2010-2018

Analysis timeframe	Years (t)	Points deforested (F_d)	Points forested	Total points (F_0)	Overall deforestation rate ($\frac{F_d}{F_0}$)	Average deforestation rate (r)
2010-2013	3	201	20792	20993	0.957%	0.319%
2010-2014	4	284	20331	20615	1.38%	0.344%
2010-2015	5	311	19817	20128	1.55%	0.309%
2010-2016	6	411	19563	19974	2.06%	0.343%
2010-2017	7	523	19214	19737	2.65%	0.379%
2010-2018	8	624	19016	19640	3.18%	0.397%

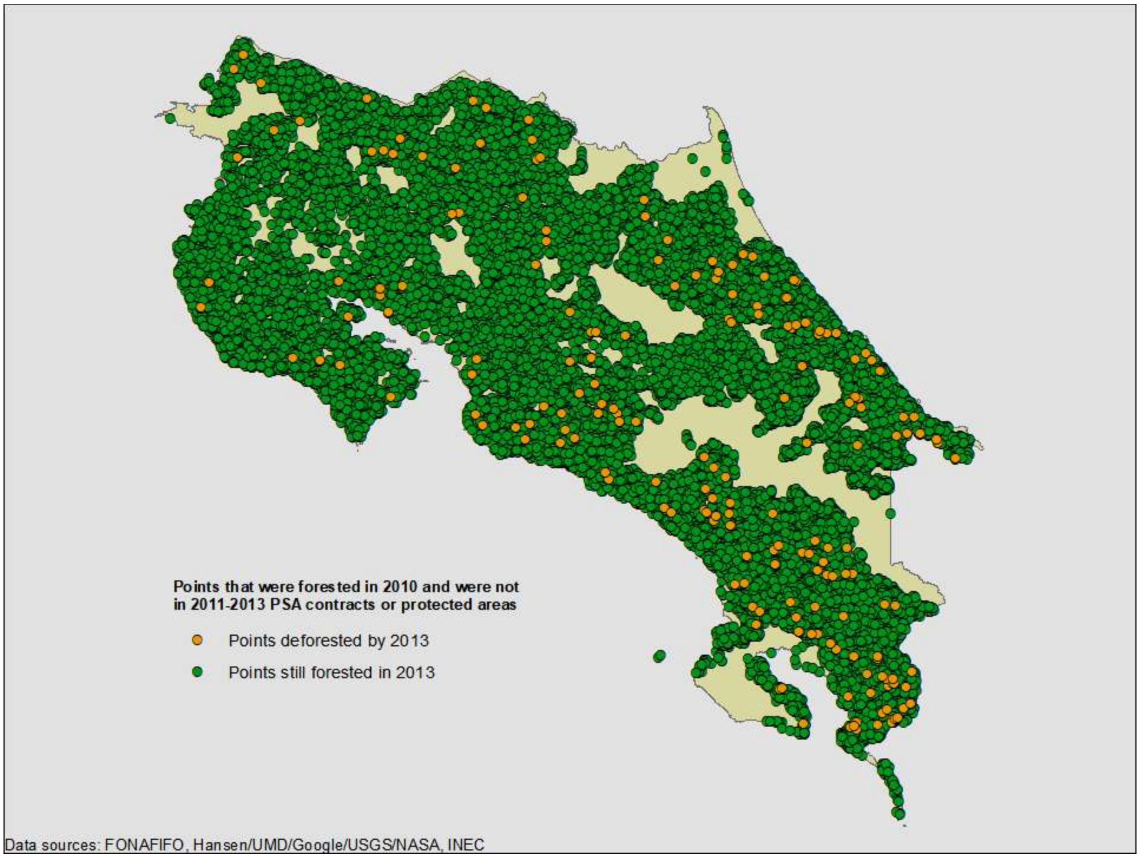

Figure 3.1: Map of non-protected non-PSA (2011-2013) 2010 forest points deforested in 2011-2013

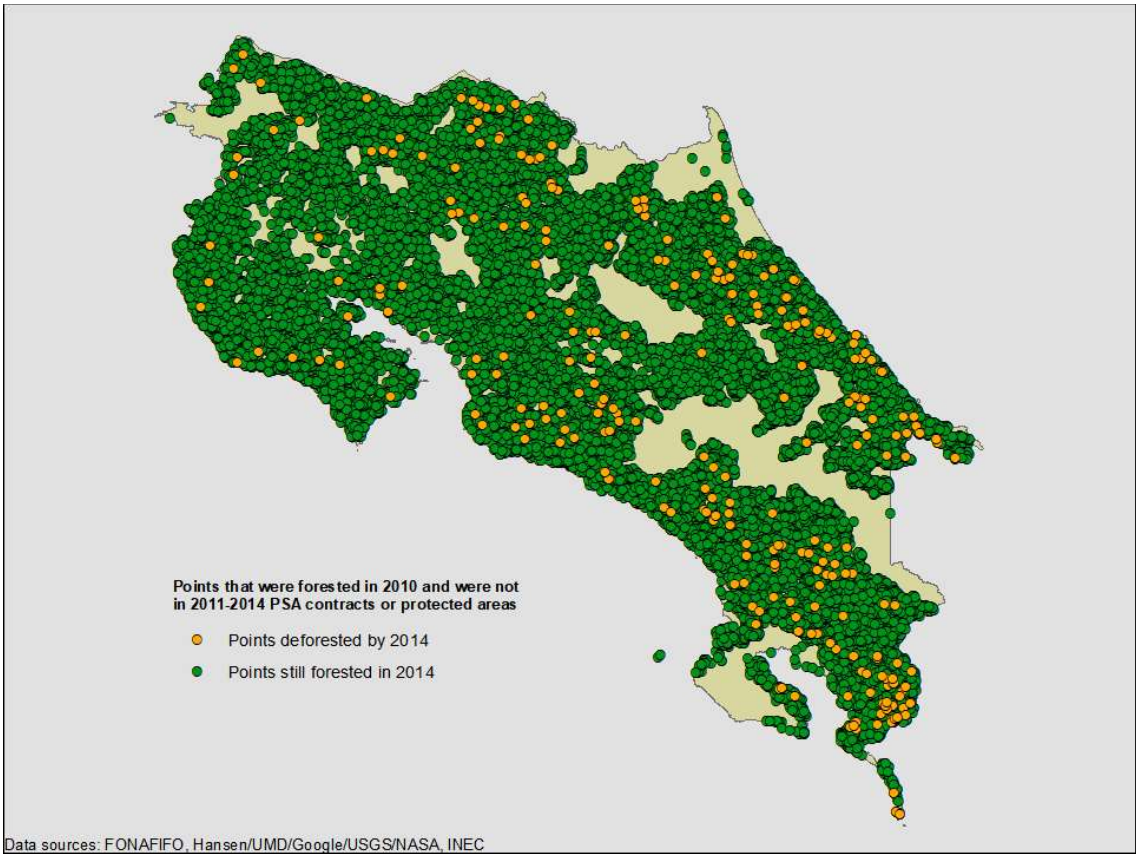

Figure 3.2: Map of non-protected non-PSA (2011-2014) 2010 forest points deforested in 2011-2014

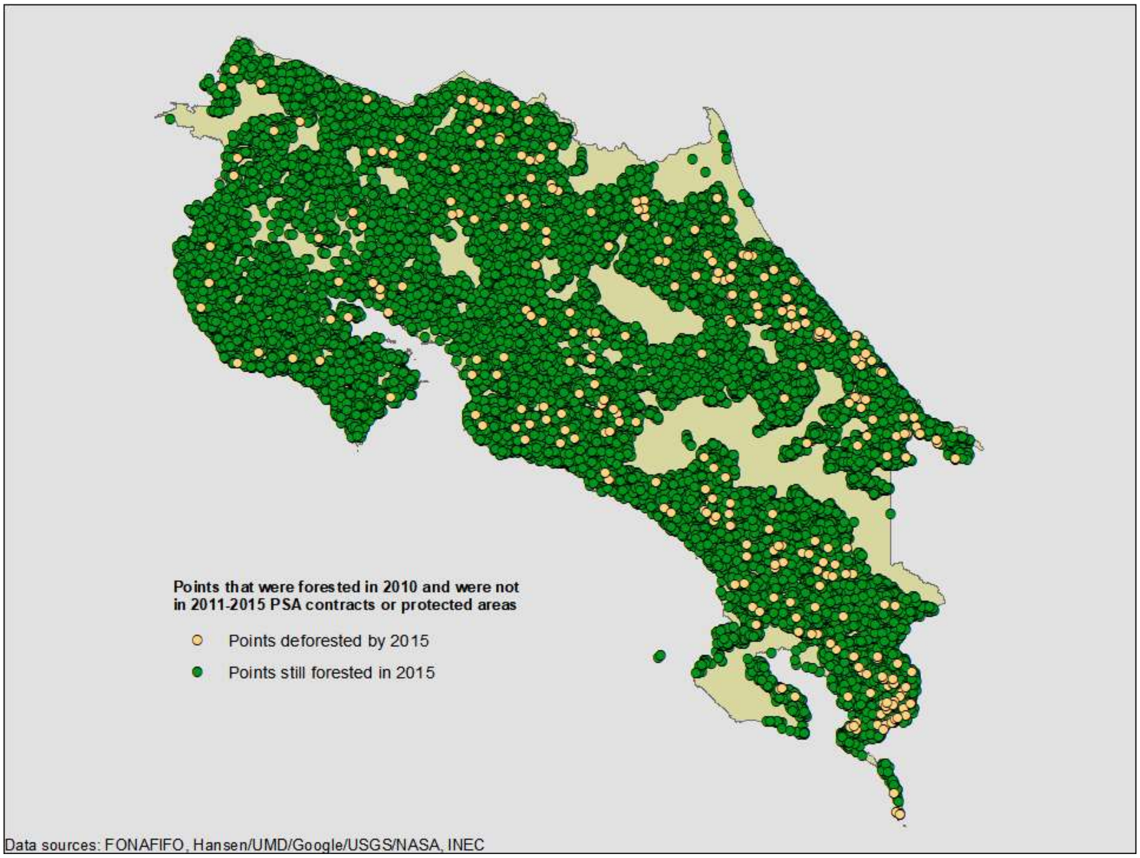

Figure 3.3: Map of non-protected non-PSA (2011-2015) 2010 forest points deforested in 2011-2015

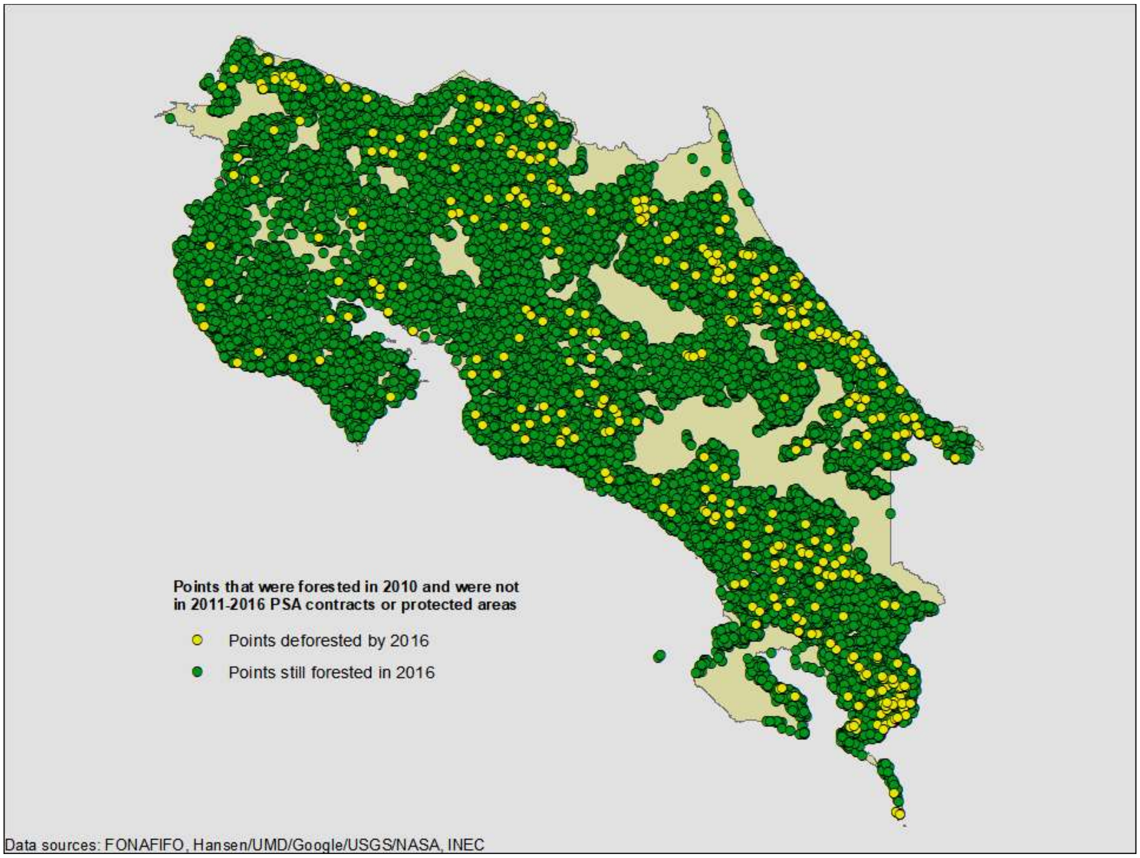

Figure 3.4: Map of non-protected non-PSA (2011-2016) 2010 forest points deforested in 2011-2016

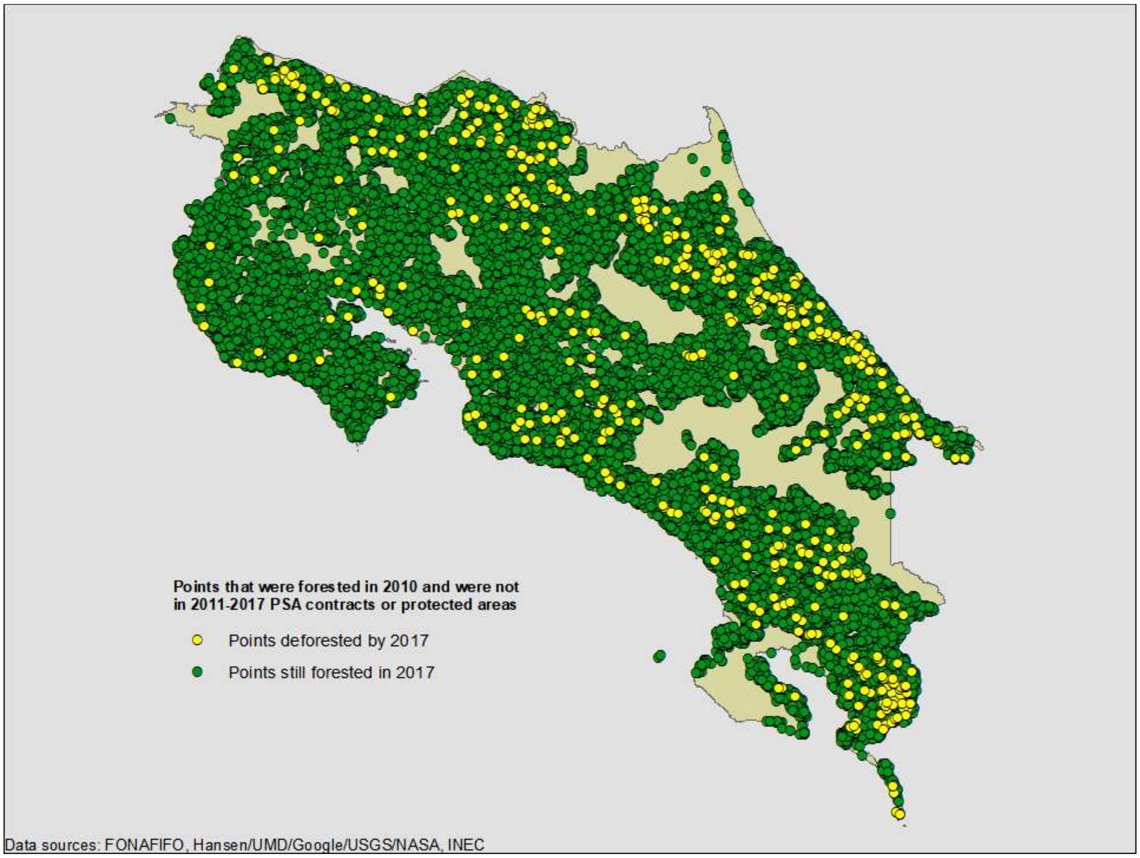

Figure 3.5: Map of non-protected non-PSA (2011-2017) 2010 forest points deforested in 2011-2017

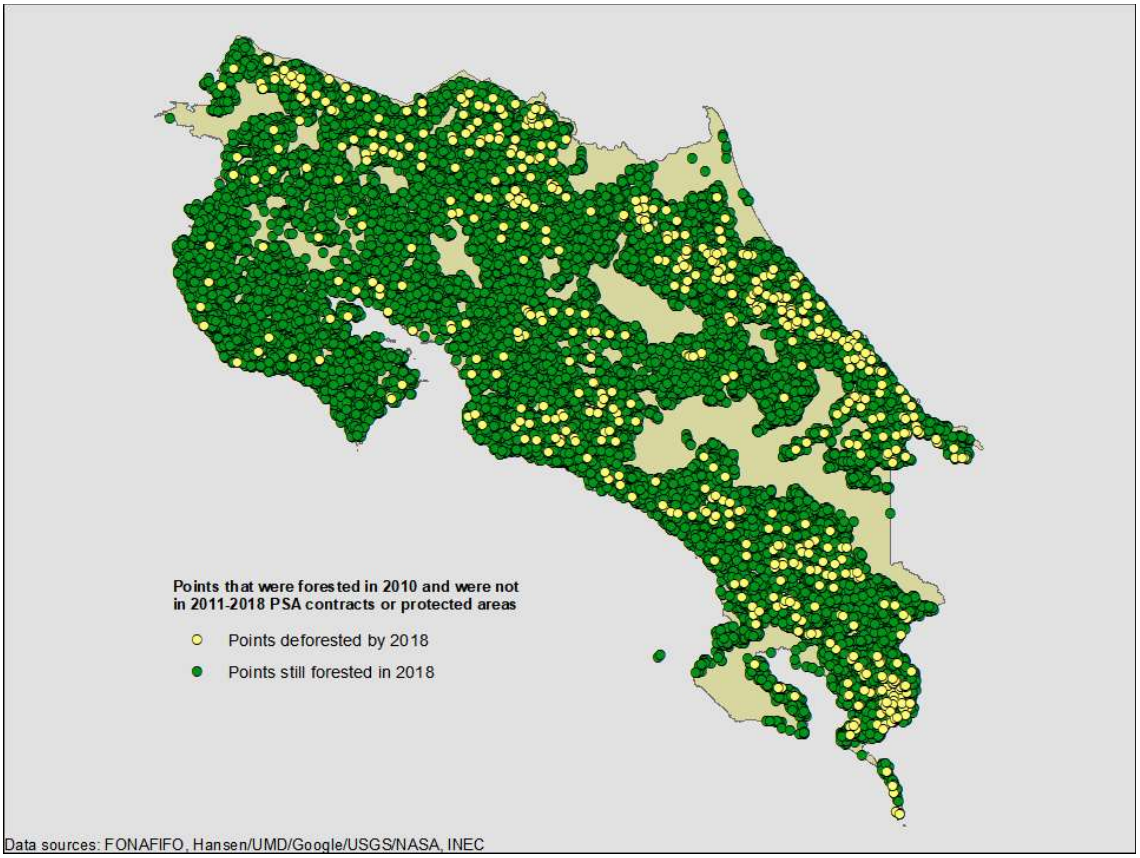

Figure 3.6: Map of non-protected non-PSA (2011-2018) 2010 forest points deforested in 2011-2018

3.5 Caveats

The following information is not yet accounted for in the above analysis.

- *Carried-over contracts from before 2011.* As described in Chapter 1, PSA contracts last for multiple years, depending on the type of contract. PSA location data was not available for contracts enacted prior to 2011. If included, this information would have excluded more points, which –

assuming those areas did not contribute to deforestation – would have resulted in a higher deforestation rate.

- *Incomplete PSA data* is a concern for some years, as mentioned in section 3.2.
- *Publicly-owned land not within protected areas.* PSA is meant for private landowners, and thus a proper comparison is with privately-owned non-PSA land, in addition to the other considerations already used to exclude points. However, private vs. non-private land ownership data was not available. If no deforestation occurred on public lands, excluding more land would probably have a similar effect as above – a higher deforestation rate would be reported due to a smaller F_0, though it's not clear whether deforestation also occurred on public lands.
- *The influence of local conditions.* Other researchers (e.g. Robalino et al. 2008) have used an econometric approach in order to do a "more similar" comparison that tries to account for differences in local conditions by picking out non-PSA points that are more similar to PSA points. The above analysis is equivalent to a "raw" analysis without the use of econometric matching methods. If matched non-PSA points exhibit more deforestation than the raw average, then the PSA would have a greater impact than appears in a raw estimate, and the PSA program would likely be well-targeted toward at-risk contract locations.

- *Inaccuracies in geographic data sources.* The reasoning here is self-evident. An example of an inaccuracy that has affected the result, albeit in a minor way, is that (according to after-the-fact visual observation) there are two points on Isla del Caño, west of the Osa Peninsula on the southern part of the country's Pacific coast. This island should be part of the Isla del Caño Biological Reserve, and thus in a protected area, but it was not properly excluded.

Caveats of this methodology are discussed more extensively in Chapter 6.

CHAPTER 4: PSA CONTRACTS AND FOREST LOSS

4.1 Introduction

While Chapter 3 attempted to estimate the deforestation rate outside PSA contracts, Chapter 4 attempts to assess instances of forest loss within PSA contracts. It would make sense to assume that there is no forest loss within PSA protection contracts, or at least no land use change, but this assumption can be examined – before, during, and after PSA contract terms. That is the purpose of this chapter's analysis. To accomplish this, forest loss data was superimposed on PSA contracts via ArcGIS in order to analyze when and how often they coincided.

In this chapter, "deforestation" and "forest loss" are used interchangeably, both referring to the lost of forest cover. However, the terms may differ substantively in other contexts: while "deforestation" may refer to mere forest loss, or to actual land use change. This analysis also does not differentiate between forest loss due to natural causes, accident, or human intention, nor does it examine reforestation or regeneration from any cause. (Consequently, caution should be exercised before using this analysis or its methods for legal purposes.) The area actively under contract in a PSA contract is unlikely to have undergone outright land use change, though this will be discussed further in Chapters 5's case studies and Chapter 6's general discussion of the findings of this research.

4.2 Data sources

The same data sources as described in section 3.2 are used, though different datasets are relevant to this chapter's analysis.

This chapter focuses not on all PSA contracts, but specifically only on the forest protection modality. As described in chapter 1, there are PSA contracts in multiple modalities, which can be grouped into five general categories, mostly recorded in hectares:

- Protección de Bosque (Forest Protection)
- Manejo de Bosque (Forest Management)
- Reforestación (Reforestation)
- Regeneración Natural (Natural Regeneration)
- Sistemas Agroforestales (Agroforestry Systems), recorded in number of trees

These are further subdivided into the subcategories shown in Table 4.1, which are represented in PSA contract data in FONAFIFO 2018. Table 4.1 sorts the contracts by modality and sub-modality, color-coded by modality. (Categorization of "Árboles en cafetales" is uncertain, as it seems to refer to agroforestry but is not measured in number of trees; this category is not relevant to the dissertation's analysis.) Not all modalities are represented in all years; those that are not are indicated by empty cells. Furthermore, sub-modalities could not be distinguished for 2016-2018 data due to data formatting errors (likely from mishandling diacritic marks on letters); category subtotals were calculated for those years where submodalities can be distinguished, for proper comparison. However, for the purpose of this analysis, all the various “protección” (protection) modalities were included; sub-modalities were not distinguished.

As shown in Table 4.1, protection contracts still make up the majority of contracts in every year, like they did in the past (Porras 2013). In this table, this modality has been bolded, as it is the focus of this analysis.

Table 4.1: Count of all PSA contracts from 2011-2018 (from FONAFIFO 2018)

PSA year (right)	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*
Árboles en cafetales (Trees on coffee plantations)			17	4				
Manejo de bosques (Forest management)	6	3	4	3	6	5	2	
PROTECTION (subtotal)	**768**	**817**	**695**	**591**	**726**	**560**	**410**	**145**
Protección areas silvestres protegidas (Protection – protected wilderness areas)	158	48	60	114	109			
Protección bosques (Protection – forests)	515	635	500	377	469			
Protección en vacios de conservación (Protection in conservation gaps)	15	30	30	16	21			
Protección recurso hídrico Protection (water resource)	80	104	105	84	127			
REFORESTATION (subtotal)	177	165	147	117	66	70	76	9
Reforestación (Reforestation)	168	159	141	112				
Reforestación especie mediano crecimiento (Reforestation – medium growth species)					52			
Reforestación especie rapido crecimiento (Reforestation – rapid growth species)					15			
Reforestación especie native (Reforestation – native species)	1	1	1		2			
Reforestación - Segundas cosechas (Reforestation – second harvests)	8	5	5	5	7			
NATURAL REGENERATION (subtotal)	25	18	32	26	23	18	23	23

Regen. nat. mdl (Natural regeneration – Clean Development Mechanism / Kyoto lands)	2							
Regeneración potreros (Natural Regeneration - pastures)	23	18	32	26	23			
Agroforestales (Agroforestry) [no category specified]	193	156	190	117	153	115	115	25
SAF café (Agroforestry – coffee)	27	59	68	89	35			
SAF esp. nat. (Agroforestry – native species)	3	8						
SAF CORFOGA (Agroforestry – Livestock Corporation)			3					
SAF especies (Agroforestry – endangered species)	2	3	3	1	1			
Total contracts	**1201**	**1229**	**1159**	**938**	**1020**	**768**	**626**	**202**

4.3 Analysis of forest loss in PSA protection contract locations: procedure and considerations

The objective of this procedure is to examine to what extent there may be deforestation in PSA contracts. But first, several considerations are important for understanding the data available.

4.3.1 Considerations

The following considerations are relevant to this analysis:

Contract lengths: Protection contracts in 2011 and 2014-2018 were paid 20% per year over a 5 year period. However, protection contracts in 2012 and 2013 were paid 10% per year over a 10 year period (FONAFIFO 2018a).

Contract geometry: PSA contract polygons as represented in GIS shapefiles are not necessarily the same size as the actual areas covered by the contract. This discrepancy is summarized in Table 4.2, which shows the discrepancy for all years aside from 2018 (which has only a small portion of PSA data, as explained in section 3.2.1 and detailed in Table 3.1). Table 4.2 accounts for the fact that contracted area reported in the attribute tables has a least significant digit of 0.1 ha (except for 2018, when it is 0.01 ha), and reports the polygon coverage correspondingly; only in 2018 (albeit with what are likely rounding errors) does the polygon coverage appear to reasonably match the contracted area coverage. There was no other data available to indicate the specific extent the contract applies to, within a given PSA polygon; only PSA contracts whose areas are roughly their polygon sizes can be assumed to be coterminous with their polygon coverage. (The polygon extents of PSA contracts in these datasets was obtained in ArcMap by adding an attribute field then using the "Calculate Geometry" function, calculating area in hectares, according to the projected coordinate system CRTM05.) Also, the distribution of PSA contract sizes is heavily skewed toward smaller contracts.

Contract counts: The slight discrepancy between protection contract counts for 2015-2018 between Table 4.1 and Table 4.2 appears to be due to the improper formatting of modality labels in those datasets. From this point forward the analysis uses only those contracts included in Table 4.2.

Table 4.2: PSA hectares contracted compared to PSA polygon coverage

Contract Year	# of contracts	Total contracted area (ha)	Average area contracted (ha)	Polygon coverage (ha)	Average polygon size (ha)	Fraction of total polygon area actually contracted
2011	768	65807.8	85.7	107291	139.7	0.613358
2012	817	62300.6	76	97364.7	119.2	0.639868
2013	695	56617.1	81.5	85244.5	122.7	0.664173
2014	581	42994	74	71340.7	122.8	0.602657
2015	726	63985.4	88.1	104997.6	144.6	0.609399
2016	554	42290.1	76.3	64230	115.9	0.658417
2017	408	40822.4	100.1	69806.4	171.1	0.584795
2018	145	15661.86	108.01	15661.18	108.01	1.000043

Double-counting and exclusion issues: Forest loss year data does not overlap – the original data source is a raster that only shows what single year within 2001-2019 (if at all) forest was lost at a given pixel, and thus there is no information on whether forest was regained then re-lost in a prior or later year. Here, this means that forest loss data in the years 2011-2019 is not available for any pixels in which forest was lost in 2001-2010. In contrast, PSA contracts are polygons set in a specific year each; these polygons have a number of overlaps between years.

Furthermore, some PSA protection contracts intersect with protected areas, as detailed in Table 4.3, though it is important to note that intersection means any overlap at all; this should not be equated to full overlaps. (Most of these were found using Select by Location in the Selection menu of ArcMap, though the 2017 PSA dataset crashed ArcMap when this was attempted; the Select Layer by Location tool in the Data Management toolbox was used instead for 2017.) Excluding these may be important for estimating the effect of PSA alone on forest protection, and so these contracts have been excluded for some of the analysis in later sections.

Table 4.3: PSA protection contracts that intersected protected areas

PSA year	Total protection contracts	Protection contracts at least partly in protected areas	Fraction of protection contracts intersecting protected areas	Contracts not intersecting protected areas
2011	768	244	0.318	524
2012	817	222	0.272	595
2013	695	227	0.327	468
2014	581	183	0.315	398
2015	726	267	0.368	459
2016	554	221	0.399	333
2017	408	161	0.395	247
2018	145	42	0.290	103

That said, just because a location is in a protected area does not mean it does not experience forest loss – see Table 4.4 and Fig. 4.1 (which graphs the third column of Table 4.4), which show that gross forest loss occurs in protected areas as well, albeit at a low rate. (Table 4.4 and Fig. 4.1 use FONAFIFO 2020 on protected areas data for maximum coverage; it is mostly similar to FONAFIFO 2018 data on protected areas.) Excluding protected areas only means excluding one possible confounding factor, at the potential cost of being less representative of PSA protection contracts altogether.

Table 4.4: Count and percentage of pixels in protected areas exhibiting deforestation in 2001-2019

Forest loss year	*Pixels*	*Percentage*
no loss	16884901	98.043%
2001-2010	120752	0.701%
2011	11104	0.064%
2012	9093	0.053%
2013	8935	0.052%
2014	13459	0.078%
2015	2740	0.016%
2016	27584	0.160%
2017	102960	0.598%
2018	18805	0.109%
2019	21655	0.126%
Total pixels in protected areas	17221988	100.000%

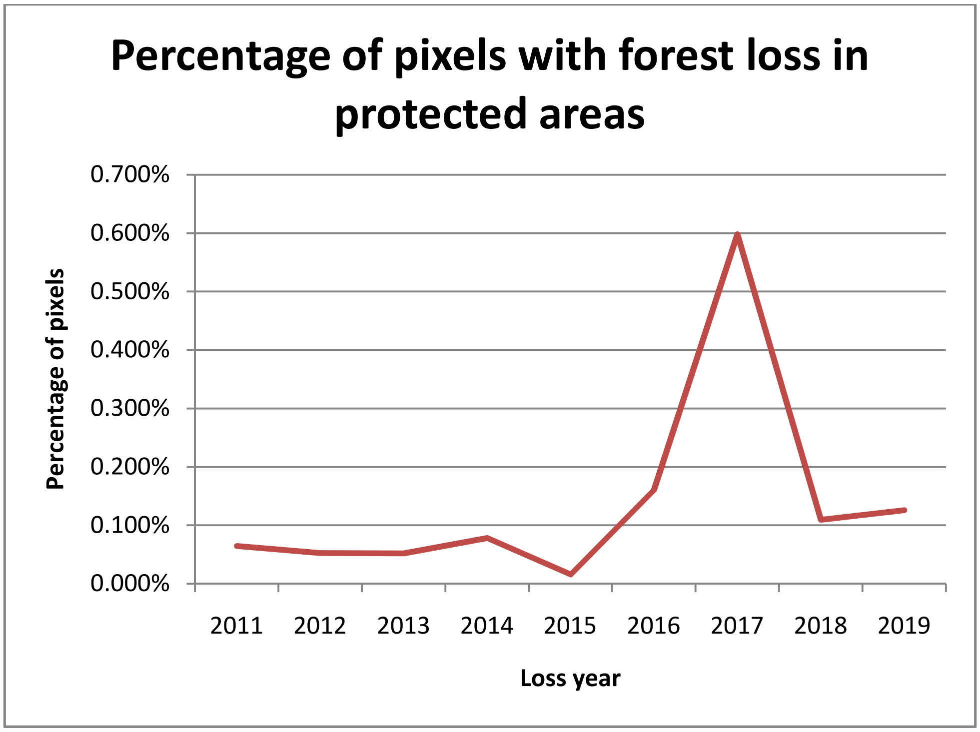

Figure 4.1 Plot of percentage of pixels in protected areas with forest loss

4.3.2 Procedure

With the aforementioned considerations in mind, the following procedure was used to perform the analysis in this chapter.

First, forest loss year raster data, converted into polygon format, was used to with Select by Location to select, then count, the PSA protection contract polygons whose geographic extent overlapped at all with any deforested pixels. (The Select Layer by Location tool was used instead of Select by Location where necessary, due to the 2017 PSA causing software crashes.) These counts were recorded, for each combination of

PSA contract year (2011-2018) and forest loss year (2001-2019). PSA contracts that intersected at all with protected areas were excluded (for now; see below).

Second, these counts were divided by the total number of PSA contracts in that contract year, in order to obtain the analogous tables that presented these figures as fractions of the total amount of PSA contracts. This was done in order to standardize the data, because different years have different amounts of PSA protection contracts. The results of this second table were graphed as a function of loss year.

There were two goals to this analysis:

1. To estimate the incidence of deforestation on the same patch of land before these PSA contracts went into effect, during PSA contract terms, and after the contracts expired. For this purpose, a highlight was added to every year the contract was assumed to be in force. For simplicity, contracts were assumed to enter into force at the beginning of their contract year, and end at the beginning of the year five or ten years later (depending on the year; see the previous section for explanation).
2. To follow the incidence of deforestation in PSA protection contract polygons, to discern whether there was a pattern of abrupt change in incidence of deforestation when areas go under contract, as having different contract years side-by-side might make it possible to visualize this. For this purpose, a graph showing loss years 2011 and onward was used.

Meanwhile, it is important to remember here is that the presence of a deforested pixel does not mean that the entire extent of the PSA contract or polygon lost forest cover. Since the aforementioned results are a PSA contract count rather than an account of area, they may over-represent the incidence of deforestation in PSA contract areas. Therefore, a second analysis was used to examine area extent.

In this second analysis, the raw loss year rasters themselves were first clipped to the extent of PSA contract polygons. This was done using the Clip tool in the Raster Processing toolset in the Data Management toolbox; the Output Extent was each year's PSA protection contract polygons, the "Use Input Features for Clipping Geometry" option was checked, while "Maintain Clipping Extent" stayed unchecked. The result was a series of rasters, one per PSA year, approximately covering *only* the extents of the PSA contracts from that year. The total pixels and deforested pixels, along with the fractions of deforested pixels out of total pixels, were then recorded and graphed, like described above.

Finally, the same steps as above were replicated in an abbreviated manner, but this time *without* excluding all PSA contracts that intersected at all with protected areas. In this abbreviated analysis, pre-2011 loss years were lumped as one category.

Besides the aforementioned analysis, a similar graph was made (for comparison), showing the deforestation fraction of the pixels covering the entire country, again graphed as a function of forest loss year. This is followed by a map showing the geographic distribution of deforested pixels. These were made using the country mask mentioned in section 3.2.1 to clip forest loss raster data.

4.4 Results

Tables 4.5(a) and 4.5(b) show, respectively, the PSA protection contract count and the fraction of total PSA contracts which intersected with each loss year's deforested pixels, for each PSA year. (As noted earlier, this excludes PSA protection contracts that intersected with protected areas.) Fig. 4.2 graphs those fractions as a progression through time as represented by forest loss years. These and subsequent tables are highlighted to represent the timeframe of a contract starting in the given contract year, as described in section 4.3.1.

These tables, particularly their bolded lines, show that PSA areas are not immune to forest loss, but when under contract, they exhibit reduced incidence of deforestation. Meanwhile, Fig. 4.3 does not show a noticeable kink (in the graphs of individual contract year lines) corresponding to when the contracts came into force. Together, these seem to suggest that the exact onset of the PSA contract may not be primary driver of the reduction in deforestation.

Tables 4.6(a) and 4.6(b) show the number deforested pixels and fraction of total pixels in PSA contracts, for each PSA year. In contrast to Table 4.5(a), the totals in Table 4.6(a) can be simply added from the rest of the table above, because there are no overlaps in pixel loss year reporting. However, since PSA contracts can overlap, each protected pixel is not necessarily unique to a contract. (Again, this excludes PSA protection contracts that intersected with protected areas, so some pixels may overlap with those contracts.) Fig. 4.3 graphs these percentages as a progression through time, again stepping through the forest loss years.

The information in Tables 4.6(a) and 4.6(b) and this figure are structured similarly to those of the previous set, but they now show a more precise picture of the deforestation rate – which appears to be less than half a percent in most years, and mainly around 0.1% to 0.3% – contrast the estimate for non-PSA lands from Chapter 3, which is about 0.320% to 0.403%. The downward trendline over time in Fig. 4.2 is no longer apparent in Fig. 4.3.

The last several rows of Table 4.6(b) calculate a deforestation rate within PSA protection contract areas in two ways: First, it averages the percentages over all the years in each time segment – before, during, and after PSA. Recognizing that some of these calculations involve comparing averages over vastly different numbers of years, this calculation was revised to only average over the five years immediately before PSA and the first five years of a (presumed) PSA contract term, for a more direct comparison. While not possible for all years, this produces deforestation rate estimates of 0.13% to to 0.32% for the five years before PSA, and 0.15% to 0.23% for the five years during PSA. The following observations can be made: (1) PSA contract areas are not immune to forest loss, but (2) the deforestation rates in both cases are low, and (3) on average they tend to decrease after enrollment in PSA, though not necessarily for any specific contract year. For the first five contract years available, the average pre-PSA five-year gross deforestation rate was calculated to be 0.244%, and the average during-PSA five-year gross deforestation rate was calculated to be 0.197%, leading to an estimated PSA protection effect of 0.047%.

The effect for 2011 contract areas can be most directly compared to the non-PSA deforestation rate obtained in Chapter 3. In this case, contract terms lasted 2011-2015, which can be compared to the 2010-2015 deforestation rate. Their during-PSA rate was 0.208%. The concurrent 2010-2015 deforestation rate was 0.309%, leading to an estimated effect of 0.101% from PSA protection.

Tables 4.7(a), 4.7(b), 4.8(a), and 4.8(b), and Figs. 4.5 and 4.6, are analogous to the above, but they include of PSA protection contracts whose geographic extent intersected protected areas, and only cover the years 2011-2019. Fig. 4.6 shows a less variable annual rate of forest loss compared to Fig. 4.4, though the values fall in a comparable range.

Finally, Fig. 4.7 shows the fraction of total pixels for the entire country, again graphed as a function of time represented by forest loss years. This can be used in comparison to Figs. 4.3 and 4.4. Fig. 4.8 offers an illustration of the distribution of forest loss pixels across the country, as covered by Fig 4.7.

There is a sharp dip in 2015 that is reflected on every graph. One might ask whether the Global Forest Change dataset, since it can only record one year timepoint of forest loss for each pixel, might have a baseline tendency to “run out” of deforestation to report, so that might explain the downward trend in apparent deforestation rate, but this trend is not actually reflected in Fig. 4.7, oddly, so this may suggest a beneficial effect of

PSA protection. However, this downward trend is not evident in Figs. 4.4 and 4.6, which arguably have slight upward trends.

While all graphs show a “dip” in loss year 2015, there is a “hump” present in 2016-2017 numbers for the entire country (Fig. 4.7, created by clipping the loss year raster against a country mask), which is absent from Figs. 4.3 and 4.5 (contract counts), but present but in more chaotic-seeming manner in Figs. 4.4 and 4.6.

The small size of these deforestation rates may be negligible in the face of background noise and regrowth – which is not accounted for because this loss year data only represents gross deforestation. While Fig. 4.7 can be used to compare pixel extents between PSA contracts and the whole country, there is no convenient non-PSA analogue for counting PSA contracts regardless of size, except possibly counting privately owned land tracts, but such data were unavailable during this analysis.

Table 4.5(a): Count of PSA protection contracts (excluding ones intersecting protected areas) that intersected deforested pixels

PSA contract year:	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	All years
No loss year	*74*	*110*	*85*	*73*	*77*	*58*	*44*	*18*	*539*
Loss year 2001	172	156	124	103	145	86	84	26	896
Loss year 2002	158	132	107	84	119	65	71	21	757
Loss year 2003	121	115	83	67	100	71	54	11	622
Loss year 2004	142	131	109	92	119	89	72	21	775
Loss year 2005	157	154	111	100	117	91	79	23	832
Loss year 2006	157	127	87	98	102	87	55	20	733
Loss year 2007	122	120	101	86	116	63	66	11	685
Loss year 2008	177	177	147	113	158	92	86	32	982
Loss year 2009	203	207	160	151	173	111	87	27	1119
Loss year 2010	147	154	115	114	119	79	76	13	817
Loss year 2011	167	140	110	101	126	83	81	23	831
Loss year 2012	125	145	99	88	107	62	56	18	700
Loss year 2013	143	121	89	78	100	70	65	16	682
Loss year 2014	126	109	101	78	95	68	61	13	651
Loss year 2015	32	33	20	13	17	12	21	5	153
Loss year 2016	76	69	63	57	53	39	27	12	396
Loss year 2017	75	94	77	48	59	38	31	11	433
Loss year 2018	91	75	69	46	61	45	36	15	438
Loss year 2019	82	67	58	53	60	43	36	8	407
Contracts with deforested pixels before PSA term	**403**	**452**	**364**	**313**	**373**	**274**	**202**	**83**	**2464**
Contracts with deforested pixels during PSA term	**315**	**302**	**215**	**145**	**140**	**97**	**63**	**18**	**1295**
Contracts with deforested pixels after PSA term	164	N/A	N/A	53	N/A	N/A	N/A	N/A	217
Total contracts	524	595	468	398	459	333	247	103	3127

Table 4.5(b): Fraction of PSA protection contracts (excluding ones intersecting protected areas) that intersected deforested pixels

PSA contract years:	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
No loss year	*0.141*	*0.185*	*0.182*	*0.183*	*0.168*	*0.174*	*0.178*	*0.175*
Loss year 2001	0.328	0.262	0.265	0.259	0.316	0.258	0.340	0.252
Loss year 2002	0.302	0.222	0.229	0.211	0.259	0.195	0.287	0.204
Loss year 2003	0.231	0.193	0.177	0.168	0.218	0.213	0.219	0.107
Loss year 2004	0.271	0.220	0.233	0.231	0.259	0.267	0.291	0.204
Loss year 2005	0.300	0.259	0.237	0.251	0.255	0.273	0.320	0.223
Loss year 2006	0.300	0.213	0.186	0.246	0.222	0.261	0.223	0.194
Loss year 2007	0.233	0.202	0.216	0.216	0.253	0.189	0.267	0.107
Loss year 2008	0.338	0.297	0.314	0.284	0.344	0.276	0.348	0.311
Loss year 2009	0.387	0.348	0.342	0.379	0.377	0.333	0.352	0.262
Loss year 2010	0.281	0.259	0.246	0.286	0.259	0.237	0.308	0.126
Loss year 2011	0.319	0.235	0.235	0.254	0.275	0.249	0.328	0.223
Loss year 2012	0.239	0.244	0.212	0.221	0.233	0.186	0.227	0.175
Loss year 2013	0.273	0.203	0.190	0.196	0.218	0.210	0.263	0.155
Loss year 2014	0.240	0.183	0.216	0.196	0.207	0.204	0.247	0.126
Loss year 2015	0.061	0.055	0.043	0.033	0.037	0.036	0.085	0.049
Loss year 2016	0.145	0.116	0.135	0.143	0.115	0.117	0.109	0.117
Loss year 2017	0.143	0.158	0.165	0.121	0.129	0.114	0.126	0.107
Loss year 2018	0.174	0.126	0.147	0.116	0.133	0.135	0.146	0.146
Loss year 2019	0.156	0.113	0.124	0.133	0.131	0.129	0.146	0.078
Contracts with deforested pixels before PSA term	**0.769**	**0.760**	**0.778**	**0.786**	**0.813**	**0.823**	**0.818**	**0.806**
Contracts with deforested pixels during PSA term	**0.601**	**0.508**	**0.459**	**0.364**	**0.305**	**0.291**	**0.255**	**0.175**
Contracts with deforested pixels after PSA term	0.313	N/A	N/A	0.133	N/A	N/A	N/A	N/A
Total contracts	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

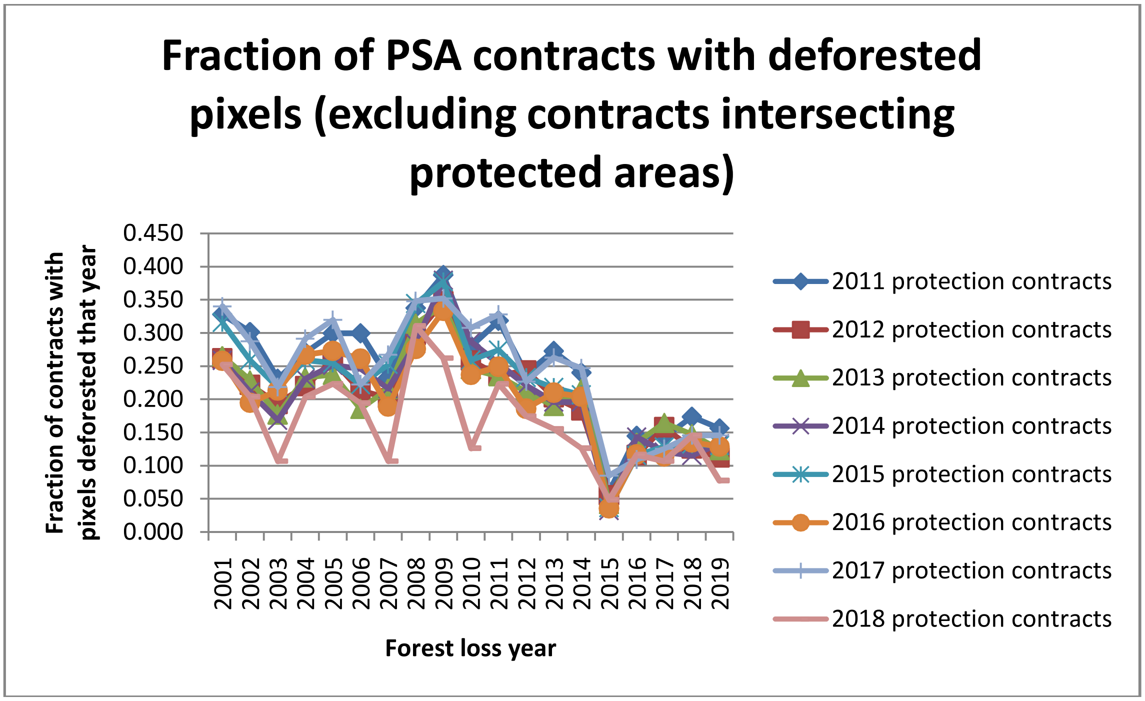

Figure 4.2: Plot of fraction of PSA protection contracts (excluding protected areas) with deforested pixels

Table 4.6(a): Count of PSA protection contract pixels (excluding PSA contracts that intersect protected areas) that were deforested pixels

PSA contract years:	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	All years
No loss year	*787530*	*756831*	*627124*	*525038*	*695363*	*378990*	*169649*	*104598*	*4045123*
Loss year 2001	2694	2240	1252	1063	1409	765	200	148	9771
Loss year 2002	1290	1187	904	646	1165	616	208	92	6108
Loss year 2003	1516	1175	1187	563	643	687	78	42	5891
Loss year 2004	2426	1141	771	671	833	1035	233	110	7220
Loss year 2005	2988	1461	1480	1028	1160	987	195	189	9488
Loss year 2006	1284	726	788	792	923	686	88	112	5399
Loss year 2007	1547	1663	1658	990	986	922	68	64	7898
Loss year 2008	4616	3058	2764	1489	1418	1260	347	218	15170
Loss year 2009	3225	2921	3967	1944	1719	1404	291	238	15709
Loss year 2010	2455	2247	1619	753	820	1513	157	66	9630
Loss year 2011	2546	943	887	754	805	584	220	116	6855
Loss year 2012	935	1116	861	742	851	461	80	112	5158
Loss year 2013	1933	1593	1191	1006	1076	1020	163	49	8031
Loss year 2014	2750	1310	1133	988	1126	1402	192	37	8938
Loss year 2015	464	177	544	84	106	355	66	52	1848
Loss year 2016	1441	1584	1454	1063	1300	1541	45	98	8526
Loss year 2017	3442	2247	3335	2234	2313	1771	160	331	15833
Loss year 2018	2108	935	3181	1347	1944	1002	359	162	11038
Loss year 2019	1762	662	1689	685	1065	687	480	159	7189
Pixels deforested before PSA term	**24041**	**18762**	**18138**	**12441**	**14934**	**13697**	**2631**	**2074**	**106718**
Pixels deforested during PSA term	**8628**	**9624**	**12527**	**5716**	**6728**	**5001**	**999**	**321**	**49544**
Pixels deforested after PSA term	8753	N/A	N/A	685	N/A	N/A	N/A	N/A	9438
Total pixels	828952	785217	657789	543880	717025	397688	173279	106993	4210823

Table 4.6(b): Percentage of PSA protection contract pixels (excluding PSA contracts that intersect protected areas) that were deforested pixels

PSA contract years:	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
No loss year	*95.003%*	*96.385%*	*95.338%*	*96.536%*	*96.979%*	*95.298%*	*97.905%*	*97.762%*
Loss year 2001	0.325%	0.285%	0.190%	0.195%	0.197%	0.192%	0.115%	0.138%
Loss year 2002	0.156%	0.151%	0.137%	0.119%	0.162%	0.155%	0.120%	0.086%
Loss year 2003	0.183%	0.150%	0.180%	0.104%	0.090%	0.173%	0.045%	0.039%
Loss year 2004	0.293%	0.145%	0.117%	0.123%	0.116%	0.260%	0.134%	0.103%
Loss year 2005	0.360%	0.186%	0.225%	0.189%	0.162%	0.248%	0.113%	0.177%
Loss year 2006	0.155%	0.092%	0.120%	0.146%	0.129%	0.172%	0.051%	0.105%
Loss year 2007	0.187%	0.212%	0.252%	0.182%	0.138%	0.232%	0.039%	0.060%
Loss year 2008	0.557%	0.389%	0.420%	0.274%	0.198%	0.317%	0.200%	0.204%
Loss year 2009	0.389%	0.372%	0.603%	0.357%	0.240%	0.353%	0.168%	0.222%
Loss year 2010	0.296%	0.286%	0.246%	0.138%	0.114%	0.380%	0.091%	0.062%
Loss year 2011	0.307%	0.120%	0.135%	0.139%	0.112%	0.147%	0.127%	0.108%
Loss year 2012	0.113%	0.142%	0.131%	0.136%	0.119%	0.116%	0.046%	0.105%
Loss year 2013	0.233%	0.203%	0.181%	0.185%	0.150%	0.256%	0.094%	0.046%
Loss year 2014	0.332%	0.167%	0.172%	0.182%	0.157%	0.353%	0.111%	0.035%
Loss year 2015	0.056%	0.023%	0.083%	0.015%	0.015%	0.089%	0.038%	0.049%
Loss year 2016	0.174%	0.202%	0.221%	0.195%	0.181%	0.387%	0.026%	0.092%
Loss year 2017	0.415%	0.286%	0.507%	0.411%	0.323%	0.445%	0.092%	0.309%
Loss year 2018	0.254%	0.119%	0.484%	0.248%	0.271%	0.252%	0.207%	0.151%
Loss year 2019	0.213%	0.084%	0.257%	0.126%	0.149%	0.173%	0.277%	0.149%
Pixels deforested before PSA term	**2.900%**	**2.389%**	**2.757%**	**2.287%**	**2.083%**	**3.444%**	**1.518%**	**1.938%**
Pixels deforested during PSA term	**1.041%**	**1.226%**	**1.904%**	**1.051%**	**0.938%**	**1.258%**	**0.577%**	**0.300%**
Pixels deforested after PSA term	1.056%	N/A	N/A	0.126%	N/A	N/A	N/A	N/A
Deforestation rate before PSA	**0.290%**	**0.217%**	**0.230%**	**0.176%**	**0.149%**	**0.230%**	**0.095%**	**0.114%**
Deforestation rate during PSA	**0.208%**	**0.136%**	**0.238%**	**0.210%**	**0.188%**	**0.252%**	**0.115%**	**0.060%**
Deforestation rate after PSA	0.264%	N/A	N/A	0.031%	N/A	N/A	N/A	N/A
Deforestation rate before PSA (5-year period)	**0.317%**	**0.276%**	**0.307%**	**0.191%**	**0.130%**	**0.192%**	**0.063%**	**0.106%**
Deforestation rate during PSA (5-year period)	**0.208%**	**0.147%**	**0.233%**	**0.210%**	**0.188%**	N/A	N/A	N/A

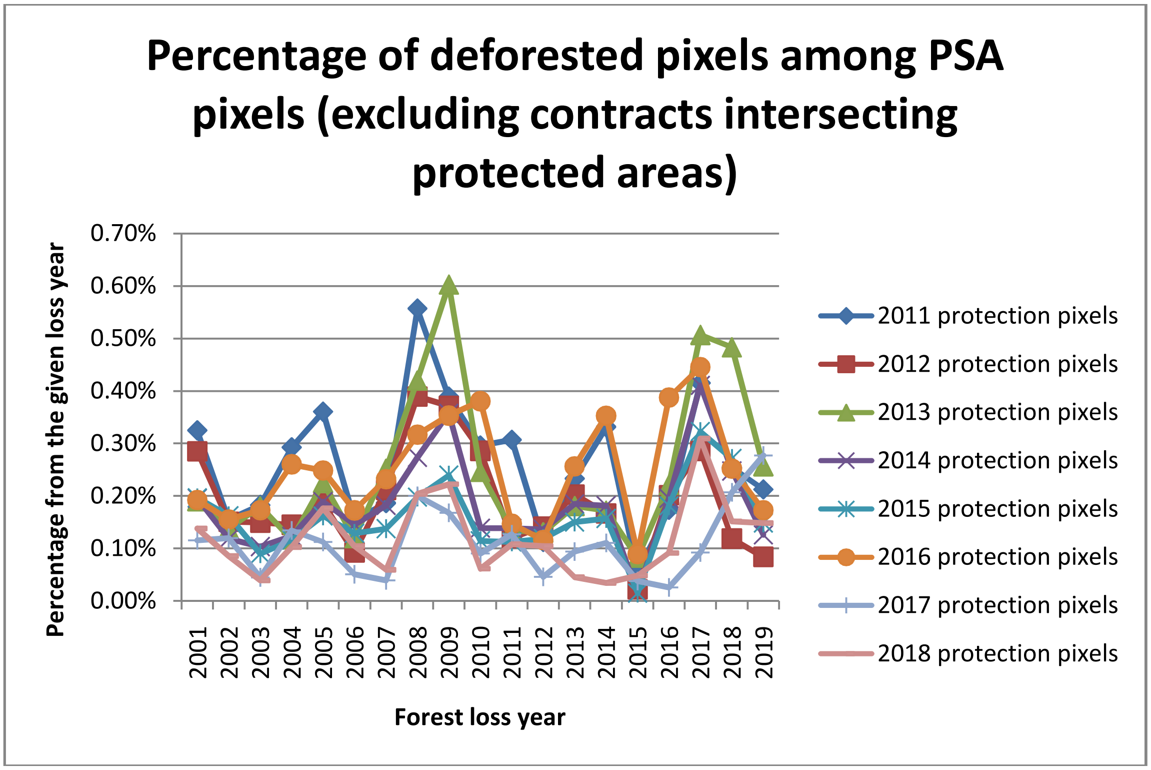

Figure 4.3: Plot of percentage of PSA protection pixel coverage (excluding protected areas) with deforested pixels

Table 4.7(a): Count of PSA protection contracts that intersected deforested pixels

PSA year	2011	2012	2013	2014	2015	2016	2017	2018
Loss year before 2011	552	602	494	406	531	384	290	99
Loss year 2011	229	197	151	153	198	139	119	35
Loss year 2012	175	194	144	127	174	110	93	26
Loss year 2013	187	158	124	111	152	105	92	23
Loss year 2014	175	160	136	118	148	102	94	25
Loss Year 2015	43	45	29	21	29	19	25	6
Loss year 2016	108	103	89	78	85	62	42	15
Loss year 2017	122	136	115	81	111	66	49	14
Loss year 2018	129	98	104	69	101	72	59	24
Loss year 2019	106	95	73	66	87	58	48	14
Total number of protection contracts	768	817	695	581	726	554	408	145

Table 4.7(b): Fraction of PSA protection contracts that intersected deforested pixels

PSA year	2011	2012	2013	2014	2015	2016	2017	2018
Loss year before 2011	0.719	0.737	0.711	0.699	0.731	0.693	0.711	0.683
Loss year 2011	0.298	0.241	0.217	0.263	0.273	0.251	0.292	0.241
Loss year 2012	0.228	0.237	0.207	0.219	0.24	0.199	0.228	0.179
Loss year 2013	0.243	0.193	0.178	0.191	0.209	0.19	0.225	0.159
Loss year 2014	0.228	0.196	0.196	0.203	0.204	0.184	0.23	0.172
Loss Year 2015	0.056	0.055	0.042	0.036	0.04	0.034	0.061	0.041
Loss year 2016	0.141	0.126	0.128	0.134	0.117	0.112	0.103	0.103
Loss year 2017	0.159	0.166	0.165	0.139	0.153	0.119	0.12	0.097
Loss year 2018	0.168	0.12	0.15	0.119	0.139	0.13	0.145	0.166
Loss year 2019	0.138	0.116	0.105	0.114	0.12	0.105	0.118	0.097

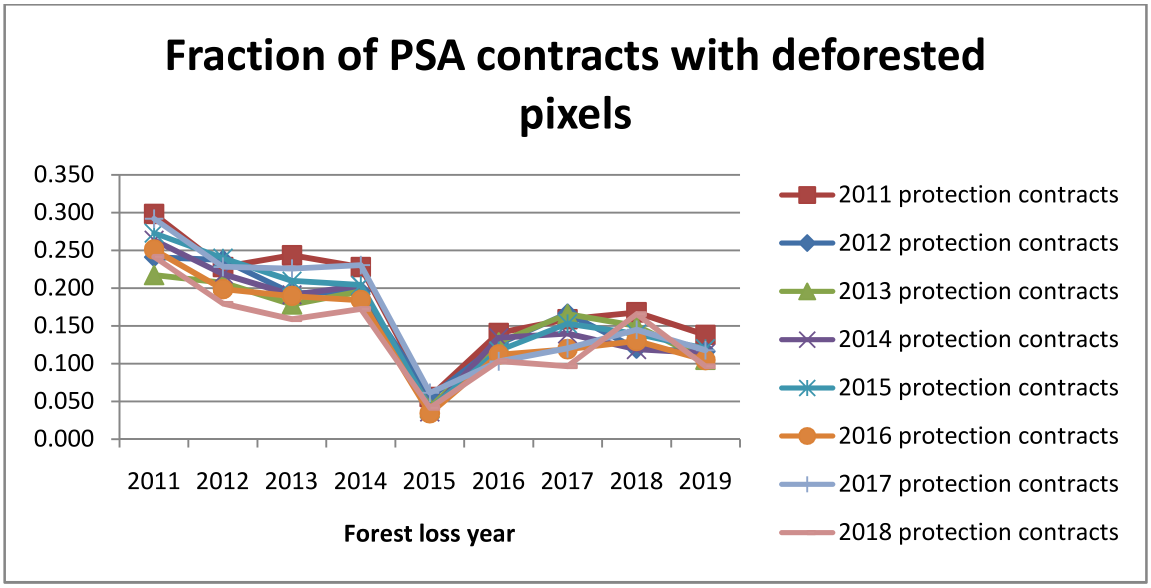

Figure 4.4: Plot of fraction of PSA protection contracts with deforested pixels

Table 4.8(a): Count of PSA protection contract pixels were deforested pixels

PSA year	2011	2012	2013	2014	2015	2016	2017	2018
Total of protection contract pixels	1409708	1280074	1120857	768008	185415	847327	223560	206513
No loss	1356709	1230524	1080653	743622	183716	811051	218958	202910
Loss year before 2011	27479	24216	19145	13037	1006	14626	2733	1683
Loss year 2011	3113	1682	1213	1587	176	1123	255	150
Loss year 2012	1229	1398	1023	1241	148	820	97	132
Loss year 2013	2184	2317	1281	718	52	1960	176	105
Loss year 2014	3173	2539	1353	1055	66	2306	200	77
Loss Year 2015	498	841	767	80	26	885	67	56
Loss year 2016	2342	7648	1993	859	17	7430	47	122
Loss year 2017	7748	4461	8078	3440	57	3401	167	705
Loss year 2018	3049	2412	3501	1631	61	2162	378	295
Loss year 2019	2184	2036	1850	738	90	1563	482	278

Table 4.8(b): Percentage of PSA protection contract pixels that were deforested pixels

PSA year	2011	2012	2013	2014	2015	2016	2017	2018
Total of protection contract pixels	1409708	1280074	1120857	768008	185415	847327	223560	206513
No loss	96.24%	96.13%	96.41%	96.82%	99.08%	95.72%	97.94%	98.26%
Loss year before 2011	1.95%	1.89%	1.71%	1.70%	0.54%	1.73%	1.22%	0.81%
Loss year 2011	0.22%	0.13%	0.11%	0.21%	0.09%	0.13%	0.11%	0.07%
Loss year 2012	0.09%	0.11%	0.09%	0.16%	0.08%	0.10%	0.04%	0.06%
Loss year 2013	0.15%	0.18%	0.11%	0.09%	0.03%	0.23%	0.08%	0.05%
Loss year 2014	0.23%	0.20%	0.12%	0.14%	0.04%	0.27%	0.09%	0.04%
Loss Year 2015	0.04%	0.07%	0.07%	0.01%	0.01%	0.10%	0.03%	0.03%
Loss year 2016	0.17%	0.60%	0.18%	0.11%	0.01%	0.88%	0.02%	0.06%
Loss year 2017	0.55%	0.35%	0.72%	0.45%	0.03%	0.40%	0.07%	0.34%
Loss year 2018	0.22%	0.19%	0.31%	0.21%	0.03%	0.26%	0.17%	0.14%
Loss year 2019	0.15%	0.16%	0.17%	0.10%	0.05%	0.18%	0.22%	0.13%

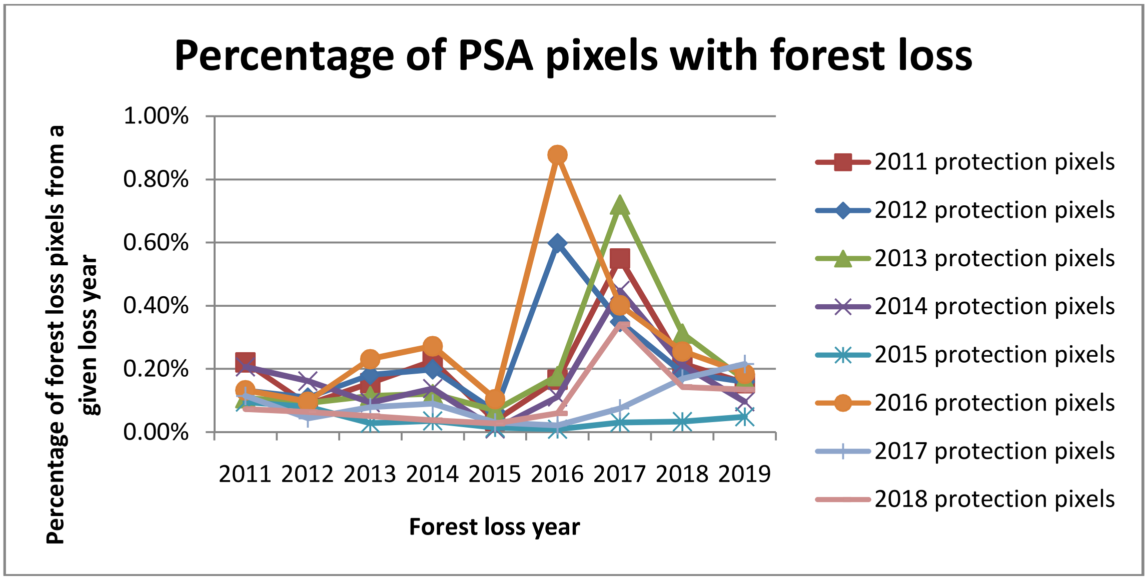

Figure 4.5: Plot of percentage of PSA protection pixel coverage with deforested pixels

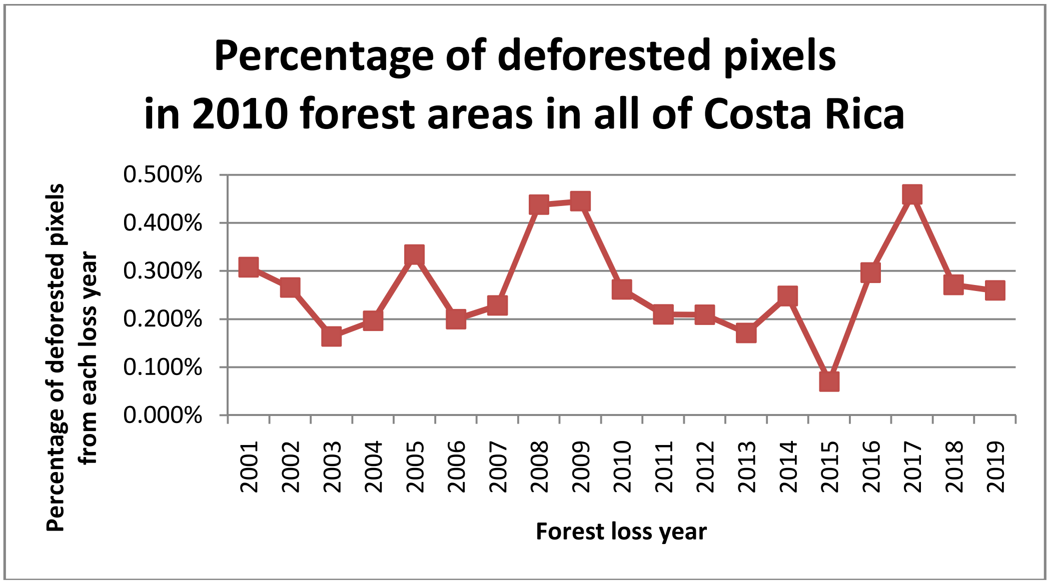

Figure 4.6: Plot of percentage of forest loss pixels in entire country, 2001-2019 (no exclusions)

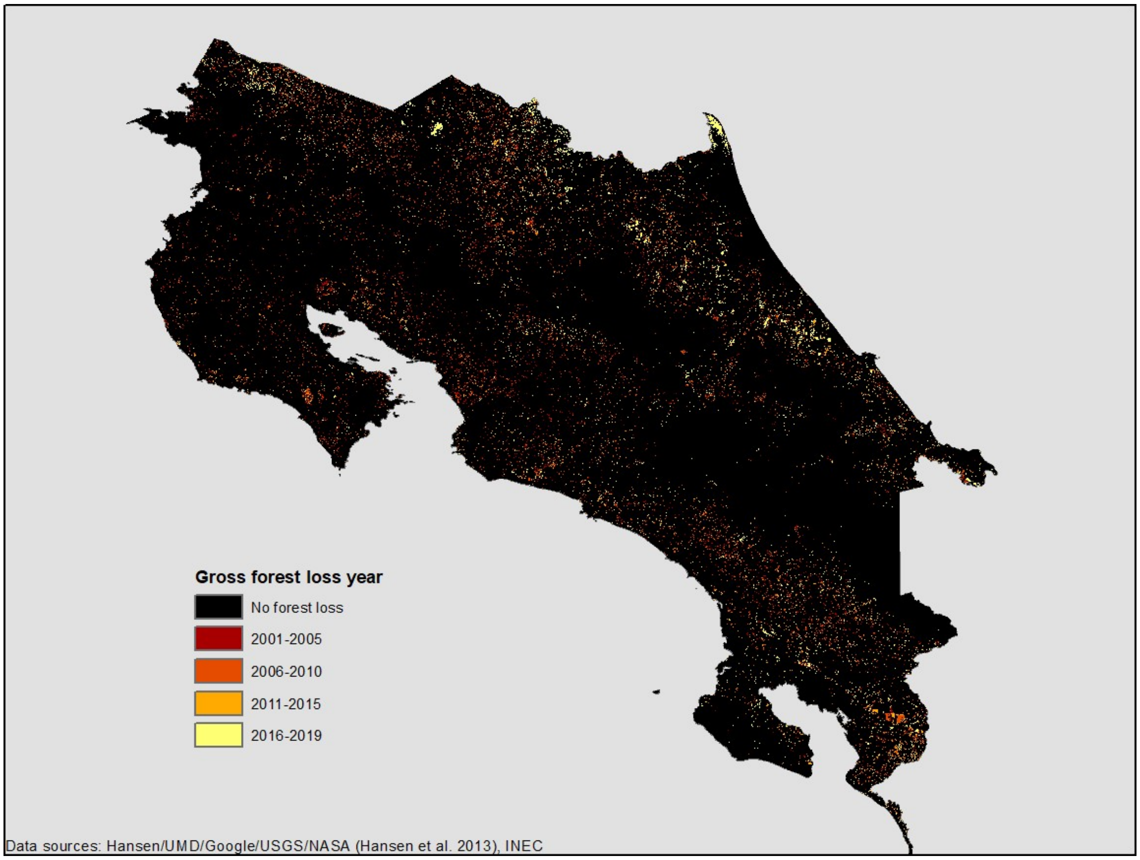

Figure 4.7: Map of distribution of deforested pixels across entire country (no exclusions)

4.5 Caveats

First, do these results really show that deforestation is happening within PSA contract areas? The extent of the area covered by the contract has been shown (in Table 4.2) to be different from that of the actual polygon coverage, the latter of which was used to find intersections with deforested pixels. Whether deforestation happened within a contract depends on where in the area the deforestation occurred.

Second, since this analysis looks solely at gross deforestation and ignores reforestation/regeneration, this analysis is unable to discern whether an event that causes deforestation causes a temporary or long-term change. Chapter 5 attempts to shed light on this by examining more detailed imagery history via Google Earth.

Third, it can be noted that Fig. 4.3 and 4.5 are arguably biased in favor of small contracts, since it is a contract count. On the other hand, Fig. 4.4 and 4.6 are arguably biased in favor of large contracts, since they are counts of geographic extent, and arguably more relevant for calculations that involve.

Fourth, because the Select by Location feature only works with polygons, it was necessary to convert the loss year raster to polygons in order to fill Tables 4.5(a) and 4.7(a). However, the raster clip function used to make Tables 4.5(b) and 4.7(b) generates clipped rasters that do not perfectly cover the polygon of a given PSA contract, leaving serrated, pixelated edges, some of which overrun or underrun the polygon boundaries. Because Select by Location counts any polygon overlap, even if a pixel polygon would not have been included in a raster clip, it may have overestimated the amount of PSA contracts with deforested pixels, relative to the raster clip method.

Finally, because forest loss year data does not overlap, it might not be proper to use a year-on-year comparison to prove that deforestation decreased.

Caveats are discussed in more detail in Chapter 6.

CHAPTER 5: REGIONAL AND LOCAL CASE STUDY FOR DEMONSTRATION

5.1 Introduction

Chapters 3 and 4 are whole-country surveys that necessarily cannot reveal geographically-specific details. Geographic variability is evidenced in various figures in Chapter 1, as well as Fig. 4.8, where different areas show different trends in deforestation as well as PSA contract activity.

Whole-country surveys can be repeated at more limited geographic extents, such as province-level, canton-level, or district-level analyses, albeit with fewer data points from which to draw generalized conclusions. At the level of region, trends with regards to forest loss patterns may be discernable and can be compared to national trends. At the level of individual PSA contracts and individual (non-PSA) locations, conditions can be analyzed in much greater spatial detail, even making of resources with less temporal consistency such as publicly-available Google Earth imagery.

As the operation to scale up such an analysis would require resources beyond those available to this researcher, this chapter serves as a demonstration. First, it examines the characteristics of a handful of PSA contracts (that do not intersect protected areas), comparing those characteristics to analogous characteristics at the national level to demonstrate regional variation, and reusing methodology from Chapter 4 for a proper comparison. Then, this chapter examines in further detail the conditions at one PSA contract location and its two nearest points (from those previously randomly selected) that are indicated as not-deforested and deforested (according to Global Forest Change loss year data), making use of Google Earth imagery in the absence of ground truthing.

5.2 Data sources and parameters for demonstration

See section 3.2 for a full list of data sources.

ArcGIS and Google Earth were used for this chapter's analysis. Google Earth was used for its historical satellite/aerial imagery, whatever was available at a scale that enabled displaying on-the-ground conditions to a reasonable level of detail, such as the extent of forests and the locations of buildings. Since the datasets mentioned in section 3.2 are in ArcGIS formats, their information needs to be transferred to Google Earth in the form of latitude/longitude coordinates, thereby allowing observation of the relevant locations' Google Earth imagery history.

For the purpose of this demonstration, locations within the tropical dry forests life zone (according to the CCT 2005 map, i.e. Bolaños et al. 2005; see Fig. 1.1) were purposely chosen. This is because this life zone is (1) among the more endangered ecosystem types threatened by deforestation, and thus this choice relates to the issue of priority, and (2) known to be more difficult to observe in remote sensing data (Kleinn et al. 2002). Furthermore, the analysis in Appendix A shows that one part of the country where deforested non-PSA points are apparently clustered in two areas, one of which is roughly in the same broad geographic region (the northwestern part of the country) as the tropical dry forest life zone. This provides an additional though ancillary reason to examine this area, though the particular PSA and no-PSA locations chosen herein actually lie somewhat to the north of the northwestern cluster of highlighted points in Fig. A.4.

When choosing locations, map displays were compared manually by approximately overlaying the GIS display and the life zones map (i.e. Bolaños et al. 2005) and switching back and forth between windows, as the latter was not available in GIS-compatible format.

A specific PSA contract was chosen according to the criteria above, as well as the additional criteria that it had relatively simple geometry, and covered a relatively small area, and was from 2011, whose 5-year contract period allowed examining post-PSA conditions. As a bonus, it had at least one deforestation pixel during 2011-2019, which made it more meaningful to examine. Nearby non-PSA points were chosen from the 50,000 random points generated for the analysis in Chapter 3. The closest point to the PSA polygon that had no deforestation in 2011-2019, and the closest point that had deforestation sometime in 2011-2019, according to Global Forest Change data, were chosen.

Ancillary data for all locations was collected from INEC data mentioned in chapter 3. Road network shapefiles did not have properly-defined coordinate systems and thus working with them was not possible at this time.

5.3 Method and results – comparison of multiple PSA parcels

This first part of the chapter's analysis focuses on how a local group of PSA contracts differ from the set of all PSA contracts as a whole, in relation to deforestation pixels. This uses some of the same methodology from the Chapter 4 (section 4.3), enabling a direct comparison.

As shown in Fig. 5.1, eleven PSA polygons, none of which intersected with protected areas, were chosen from the northwestern part of the country, roughly corresponding to the northernmost patch of yellow in Fig. 1.1. The specially-highlighted PSA contract and the two nearby non-PSA points were used for the analysis in section 5.4; this particular PSA contract was included among those for analysis here in section 5.3.

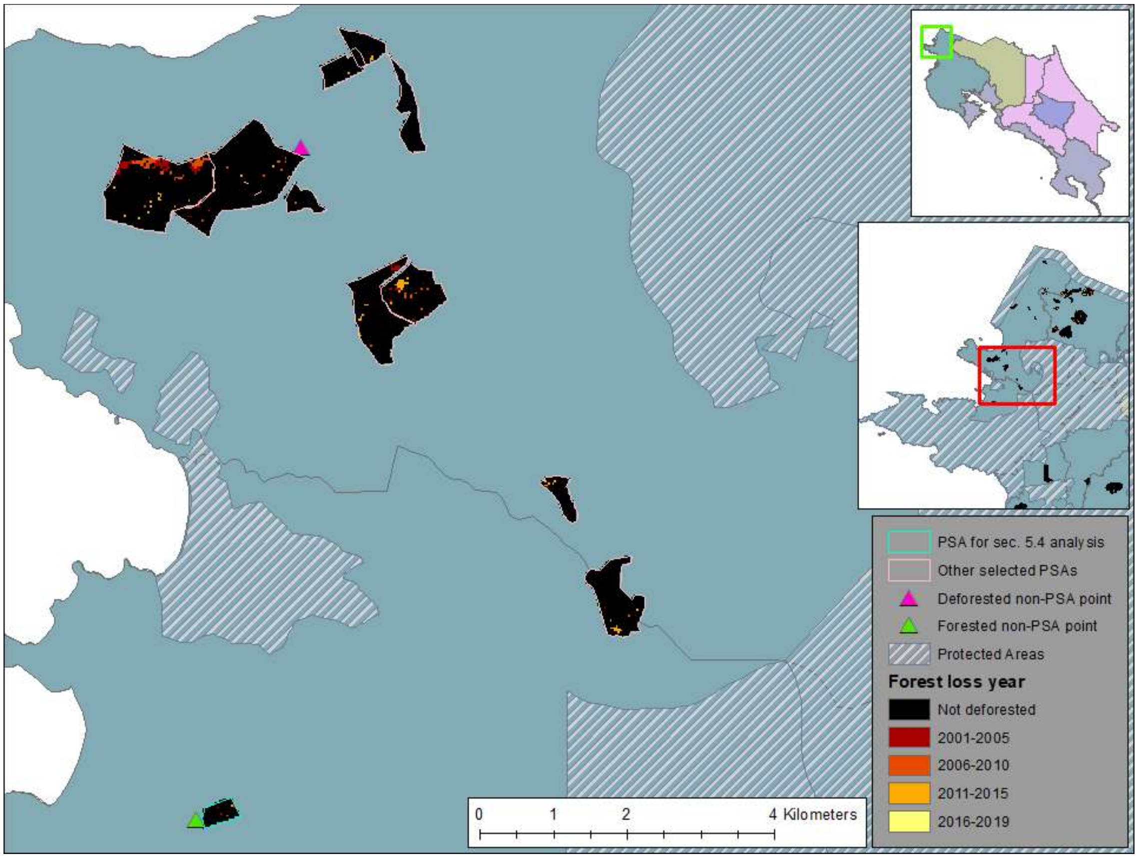

Figure 5.1: Map of 11 selected contracts and selected non-PSA points

These contracts are unevenly distributed amongst the several contract years, as shown in Table 5.1, which shows the incidence of deforested pixels in this group of PSA polygons, and is intentionally laid out analogously to Table 4.5(a). Analogues to Table 4.5(b) and Fig. 4.2 are not included here because the number of contracts is too few to be particularly meaningful. For this method of analysis, a larger number of contracts would be useful. However, even with only eleven contracts, their pixel counts can be viably compared.

Table 5.1: Count of selected PSA contracts that intersected deforested pixels

PSA contract years:	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	All years
No loss year	*0*	*1*	*0*	*0*	*0*	*N/A*	*N/A*	*0*	*1*
Loss year 2001				1					
Loss year 2002	1			2					
Loss year 2003				1					
Loss year 2004	2		1	3	1				
Loss year 2005									
Loss year 2006				1					
Loss year 2007	2		1	2	1				
Loss year 2008									
Loss year 2009				1					
Loss year 2010				1	1				
Loss year 2011									
Loss year 2012									
Loss year 2013	2		1	3	1				
Loss year 2014								1	
Loss year 2015					1				
Loss year 2016									
Loss year 2017									
Loss year 2018									
Loss year 2019									
Contracts with deforested pixels before PSA term	**2**	**0**	**1**	**3**	**1**	**N/A**	**N/A**	**1**	**8**
Contracts with deforested pixels during PSA term	**2**	**0**	**1**	**0**	**1**	**N/A**	**N/A**	**0**	**4**
Contracts with deforested pixels after PSA term	0	N/A	N/A	0	N/A	N/A	N/A	1	1
Total contracts	2	1	1	3	3	0	0	1	11

As shown in Tables 5.2(a) and 5.2(b), the same pixel-based analysis used for Figs. 4.6(a) and 4.6(b) can be applied, even for a small number of contracts such as this. Table 4.6(b) in particular can be used to estimate the in-PSA deforestation rate; the average even with a coverage of just 6235 pixels (2011-2015 contract years here, which is most of the dataset). The average deforestation rates for standardized five-year periods immediately before and during a PSA are 0.134% and 0.066%, respectively, giving a before-and-after comparison improvement of 0.068%. When the latter is compared to the estimated national non-PSA deforestation rate of 0.309% (for 2010-2015), the improvement is 0.243%. Meanwhile, when looking at 2011 contracts only, a before-and-during comparison appears to increase that the rate from 0.042% to 0.228%, though for a direct comparison to that deforestation rate for 2011-2015, there is still an improvement of 0.081% over the national level. These results can serve as estimates of the impacts in reduced deforestation due to these particular PSA contracts.

Table 5.2(a): Count of pixels in 11 selected contracts that were deforested pixels

PSA contract years:	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	All years
No loss year	*931*	*325*	*1518*	*2142*	*1048*	*N/A*	*N/A*	*236*	*6200*
Loss year 2001				11					*11*
Loss year 2002	3			19					*22*
Loss year 2003				1					*1*
Loss year 2004	16		4	41	1				*62*
Loss year 2005									*0*
Loss year 2006				3					*3*
Loss year 2007	2		10	84	1				*97*
Loss year 2008									*0*
Loss year 2009				1					*1*
Loss year 2010				1	1				*2*
Loss year 2011									*0*
Loss year 2012									*0*
Loss year 2013	11		2	43	12				*68*
Loss year 2014								1	*1*
Loss year 2015					4				*4*
Loss year 2016									*0*
Loss year 2017									*0*
Loss year 2018									*0*
Loss year 2019									*0*
Pixels deforested before PSA term	**21**	**0**	**14**	**204**	**15**	**0**	**0**	**1**	**255**
Pixels deforested during PSA term	**11**	**0**	**2**	**0**	**4**	**0**	**0**	**0**	**17**
Pixels deforested after PSA term	0	N/A	N/A	0	N/A	N/A	N/A	N/A	0
Total pixels	963	325	1534	2346	1067	0	0	237	6472

Table 5.2(b): Percentage of pixels in 11 selected contracts that were deforested pixels

PSA contract years:	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
No loss year	*96.68%*	*100%*	*98.96%*	*91.30%*	*98.22%*			*99.58%*
Loss year 2001	0	0	0	0.47%	0			0
Loss year 2002	0.31%	0	0	0.81%	0			0
Loss year 2003	0	0	0	0.04%	0			0
Loss year 2004	1.66%	0	0.26%	1.75%	0.09%			0
Loss year 2005	0	0	0	0	0			0
Loss year 2006	0	0	0	0.13%	0			0
Loss year 2007	0.21%	0	0.65%	3.58%	0.09%			0
Loss year 2008	0	0	0	0	0			0
Loss year 2009	0	0	0	0.04%	0			0
Loss year 2010	0	0	0	0.04%	0.09%			0
Loss year 2011	0	0	0	0	0			0
Loss year 2012	0	0	0	0	0			0
Loss year 2013	1.14%	0	0.13%	1.83%	1.12%			0
Loss year 2014	0	0	0	0	0			0.42%
Loss year 2015	0	0	0	0	0.37%			0
Loss year 2016	0	0	0	0	0			0
Loss year 2017	0	0	0	0	0			0
Loss year 2018	0	0	0	0	0			0
Loss year 2019	0	0	0	0	0			0
Pixels deforested before PSA term	**2.18%**	**0**	**0.91%**	**8.70%**	**1.41%**			**0.42%**
Pixels deforested during PSA term	**1.14%**	**0**	**0.13%**	**0**	**0.37%**			**0**
Pixels deforested after PSA term	0	N/A	N/A	0	N/A	N/A	N/A	N/A
Deforestation rate before PSA	**0.218%**	**0**	**0.076%**	**0.67%**	**0.100%**	N/A	N/A	**0.025%**
Deforestation rate during PSA	**0.228%**	**0**	**0.016%**	**0**	**0.075%**	N/A	N/A	**0.000%**
Deforestation rate after PSA	0	N/A	N/A	0	N/A	N/A	N/A	N/A
Deforestation rate before PSA (5-year period)	**0.042%**	**0**	**0**	**0.38%**	**0.244%**	N/A	N/A	**0.084%**
Deforestation rate during PSA (5-year period)	**0.228%**	**0**	**0.026%**	**0**	**0.075%**	N/A	N/A	N/A

For a further illustration of regional differences from national rates, Table 5.3 compares the pixel distributions of these eleven contracts and all the forest protection contracts (excluding those intersecting protected areas) in the country as a whole. There is a quick calculation at the bottom, using these forest loss year records to estimate annual deforestation rate before and including/after 2011, using Equation 3.3. While not all contracts began in that year, this serves as a quick estimate showing that there was a reduction in deforestation rate between the decades, and this reduction differs based on geography: 0.025% for PSA protection contracts (not intersecting protected areas) in the country as a whole, 0.183% for these eleven contracts.

The distribution over time of deforested pixels over time is shown as a percentage for each contract (where “Contract 00” is the contract examined in section 5.4) in Fig. 5.2(a) and as an aggregate sum across all eleven contracts in Fig. 5.2(b). The latter figure can be directly compared to Fig. 5.3, which shows the temporal distribution of forest loss pixels in PSA protection contracts (not intersecting protected areas) across the entire country. Easily visible are the differences in the distributions, especially the entire absence or near-absence of deforested pixels from certain loss years. Finally, the mean, median, and standard deviation of loss year are shown in Table 5.5, showing another way to quantifying this difference in distributions.

Table 5.3: Pre-2011 and post-2011 deforestation rates within PSA protection contracts (not intersecting protected areas) for 11 selected contracts vs. the whole country

Loss year	Forest loss pixels (11 contracts)	Fraction of total	Annual deforestation rate (%)	Forest loss pixels (whole country PSAs)	Fraction of total	Annual deforestation rate (%)
Not deforested	6165	0.9577		3495606	0.96095	
2001	11	0.00171		8778	0.00241	
2002	22	0.00342		5317	0.00146	
2003	1	0.00016		5010	0.00138	
2004	62	0.00963		6103	0.00168	
2005	0	0.00000		8656	0.00238	
2006	3	0.00047		4703	0.00129	
2007	97	0.01507		6547	0.00180	
2008	0	0.00000		13038	0.00358	
2009	1	0.00016		13275	0.00365	
2010	2	0.00031		8231	0.00226	
2011		0.00000		6337	0.00174	
2012		0.00000		4743	0.00130	
2013	68	0.01056		6592	0.00181	
2014	1	0.00016		7845	0.00216	
2015	4	0.00062		1830	0.00050	
2016		0.00000		7560	0.00208	
2017		0.00000		12632	0.00347	
2018		0.00000		8508	0.00234	
2019		0.00000		6342	0.00174	
Total pixels	6437	1.00000		3637653	1.00000	
Pixels w/LY	272	0.04226	0.227%	142047	0.03905	0.209%
Pixels w/LY 2010-	199	0.03092	0.314%	79658	0.02190	0.221%
Pixels w/LY 2011+	73	0.01134	0.131%	62389	0.01715	0.196%

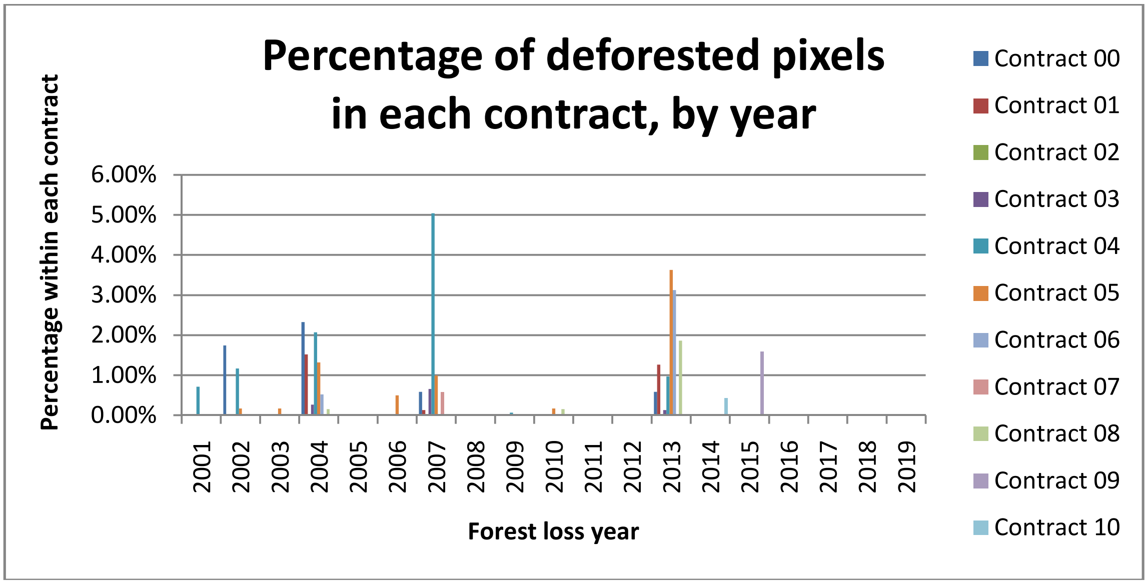

Figure 5.2(a): Histogram of percentage of loss year pixels by year, in each selected contract

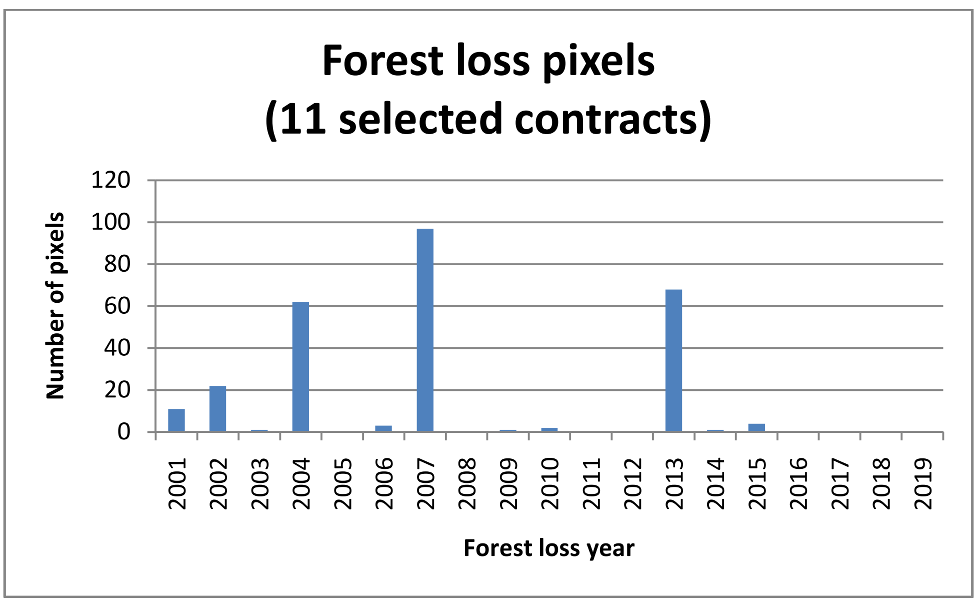

Figure 5.2(b): Histogram of loss year pixels by year, aggregated over 11 selected contracts

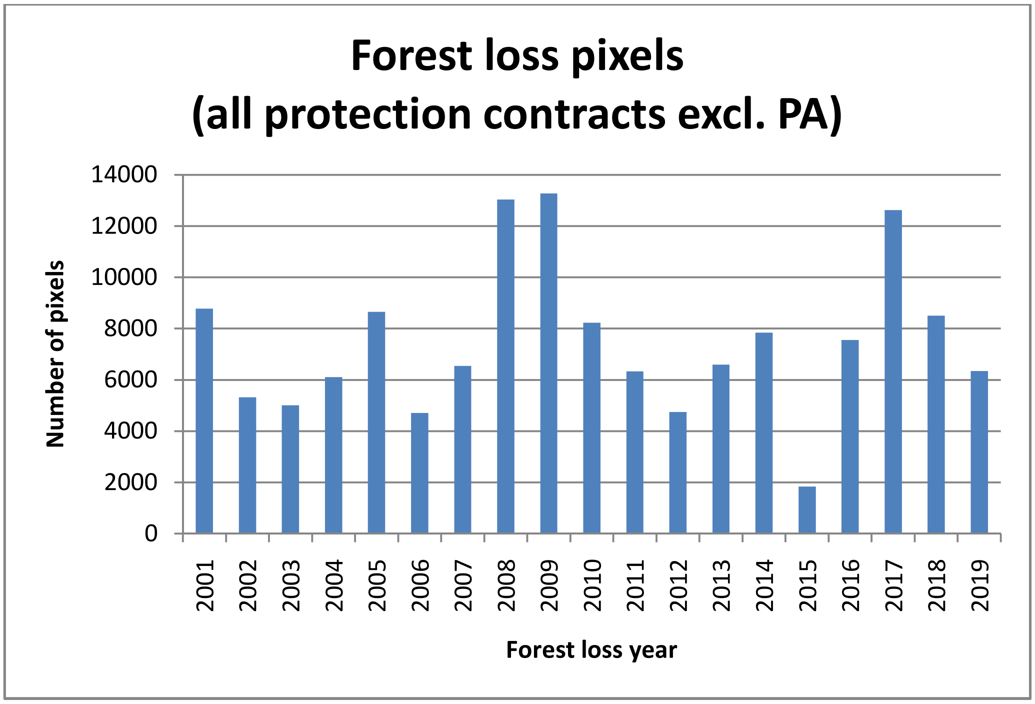

Figure 5.3: Histogram of loss year pixels by year, across all PSA protection contracts (not intersecting with protected areas) in the entire country

Table 5.4 Basic loss year statistics comparing 11 selected PSAs to (protection modality, not intersecting protected areas) PSAs in the whole country

	Selected PSAs	Whole country PSAs
Mean loss year (2001-2019)	2007.316	2010.146
Median loss year (2001-2019)	2007	2008
Standard deviation	3.963	5.395

5.4 Method and results – PSA comparison to nearest random points

The purpose of this second part of the procedure was to demonstrate the use and limitations of Google Earth imagery for assessing the land cover conditions in a specific PSA contract location and two nearby non-PSA points. The procedure here basically consisted of three steps: (1) determining the location coordinates of the three features (PSA polygon, non-PSA non-deforested point, and non-PSA deforested point), (2) transferring the location data to Google Earth, and (3) examine the image history available at those locations. Along the way, ancillary data for the locations was also collected from INEC sources, as mentioned above, to provide additional context and demonstration if needed.

The locations of these three features are illustrated in Fig. 5.1. In order to determine these locations, latitude and longitude coordinates were calculated in ArcMap by adding new columns to the attribute table containing the features in question and using the Calculate Geometry feature to determine the Y (latitude) and X (longitude) coordinates in decimal degrees. This was done because Google Earth uses latitude and longitude coordinates as inputs for specifying location. (While Google Earth also takes Universal Transverse Mercator coordinates, the analysis so far has not used a UTM coordinate system.) The Calculate Geometry function was also used to obtain the centroid of the random PSA point as well as the spatial coverage (area) of the PSA polygon. Nearby points were selected from the random point pool manually, because the closest points happened to be conveniently obvious when displayed in ArcMap (and even if they were not, ArcMap has tools to handle this). In order to obtain coordinates for the vertices of the PSA polygon, the vertices were first determined using the Feature Vertices to Points tool (in the Data Management toolbox).

The following PSA contract was chosen for this demonstration:

- contract#: CA-01-22 -0073-2011
- contract modality/submodality: forest protection (no subcategory)
- year: 2011 (contract length: 5 years)
- contracted hectares: 0 (There is one lone 2011 PSA protection contract that has the number "0" for its "has_psa" (i.e. hectares in PSA) field, and it happens to be this one; all others had at least 2 hectares under contract. No matter; this highlights the usefulness of looking at the data in great detail.)
- PSA polygon hectares: 12.87409
- Coordinates of PSA polygon vertices: shown in Table 5.5.
- Centroid: 10.933976° N, 85.684388° W
- Nearest non-PSA random point with no forest loss: 10.933146° N, 85.687212° W
- Nearest non-PSA random point with forest loss: 11.015673° N, 85.674687° W
- Nearest non-PSA random point with forest loss, loss year: 2015

Table 5.5: Latitude/longitude of demonstration PSA polygon vertices

Latitude	Longitude
10.9335° N	85.6818° W
10.9321° N	85.6864° W
10.93233° N	85.6864° W
10.93281° N	85.6865° W
10.93292° N	85.6865° W
10.93334° N	85.6866° W
10.93358° N	85.6866° W
10.93451° N	85.6864° W
10.93464° N	85.6861° W
10.93561° N	85.6839° W
10.93584° N	85.683° W
10.93355° N	85.6818° W

Ancillary information about them is detailed in Table 5.6. More such ancillary details can be examined – for example, an analysis could exclude inactive sawmills (the one shown here is indicated to be such), or examine distance to the nearest international airport (as international travel is a major part of ecotourism) – but this is not the focus of the present demonstration. These can be used for other subdivisions for analysis of the pool of all PSA contracts. And while in here Table 5.2 illustrates the similarities between the points, in econometric analyses (such as Robalino et al. 2011) these attributes are used to choose intentionally similar points in order to eliminate confounding variables. Additionally, intentionally choosing different points may reveal contrasts between PSA and non-PSA locations, or differences-in-differences when comparing various regions.

Table 5.6: Ancillary data for chosen demonstration locations

	Demonstration PSA location	Nearest non-PSA random point without deforestation	Nearest non-PSA random point with deforestation
Conservation Area	Guanacaste	Guanacaste	Guanacaste
Province	Guanacaste	Guanacaste	Guanacaste
Canton	La Cruz	La Cruz	La Cruz
District	Santa Elena	La Cruz	La Cruz
Pixel deforested in (year)	1 of 172 pixels deforested in 2013 (8 other pixels deforested before 2011)	(Not deforested in 2001-2019)	2015
Distance from nearest airport	4143 (to Murciélago, MRMC)	Murciélago (MRMC) or La Flor (MRLF)	Murciélago (MRMC) or La Flor (MRLF)
Distance from nearest protected area (FONAFIFO 2020)	2019 m (to Bahía Junquillal)	2415 m (to Bahía Junquillal)	3135 m (to Chenailles)
Distance from nearest sawmill	16042 m (to Aserradero Sapoa S.A.)	16482 (to Asseradero Sapoa S.A.)	7711 m (to Aserradero Sapoa S.A.)
Distance from nearest city	16034 m (to La Cruz)	16476 m (to La Cruz)	7724 m (to La Cruz)
Elevation	0 m to 100 m	0 m to 100 m	0 m to 100 m
Precipitation (2014 mean annual precipitation)	1500 mm to 2000 mm	1500 mm to 2000 mm	1500 mm to 2000 mm

The main focus of this section is the time series presented in Figs. 5.4 and 5.5, which show the imagery history in Google Earth for the PSA polygon and nearest non-PSA non-deforested point (Fig. 5.4, pictured together because they were close together) and nearest non-PSA deforested point (Fig. 5.5). These images were obtained by copying the coordinates of each non-PSA point, and the coordinates of the vertices of the PSA polygon, into Google Earth, and zooming into the area to examine conditions. Since Google Earth does not allow specifying the coordinates of polygon vertices, the vertices had to be entered in the form of individual points, shown as green pegs in Fig. 5.4 – hence the preference for a simple polygon. Some imagery was skipped (both locations' imagery history have a very low-resolution image dated December 1969).

The dynamics of the dry forest can be seen in Fig. 5.4, especially Fig. 5.4(f), which was taken in May 2013. The dry season in these tropical dry forests lasts from late December to mid-May (Arroyo-Mora et al. 2005), and trees become defoliated during that time.

Figs. 5.4(e) and 5.4(i) appear to be mosaics combining some new imagery with imagery from the previous timestamp, demonstrating a caveat of Google Earth imagery data.

With regards to the PSA contract period, the PSA polygon shown here was for a 2011 contract, which lasts five years. Depending on when it began, it may or may not include the November 2016 image, and depending on its spatial extent (reported to be 0 hectares for unidentified reasons), it may or may not include the area near the northern edge which seems to have experienced some clearing starting in November 2016 – or possibly as early as May 2013. This clearing expanded in 2017-2018, and eventually buildings were present in that area in December 2018. Thus, this may be evidence of post-PSA deforestation (depending on the actual area of the contract). That said, Calvo-Alvarado et al. (2009) mentions that maintaining "access trails" is part of a PSA protection contract, so some of the clearing may be part of the contract itself.

Figure 5.4(a): Demonstration PSA location and non-PSA/non-deforested random point in February 2004

Figure 5.4(b): Demonstration PSA location and non-PSA/non-deforested random point in August 2008

Figure 5.4(c): Demonstration PSA location and non-PSA/non-deforested random point in September 2009

Figure 5.4(d): Demonstration PSA location and non-PSA/non-deforested random point in October 2010

Figure 5.4 (e): Demonstration PSA location and non-PSA/non-deforested random point in January 2013

Figure 5.4(f): Demonstration PSA location and non-PSA/non-deforested random point in May 2013

Figure 5.4(g): Demonstration PSA location and non-PSA/non-deforested random point in January 2014

Figure 5.4(h): Demonstration PSA location and non-PSA/non-deforested random point in February 2014

Figure 5.4(i): Demonstration PSA location and non-PSA/non-deforested random point in November 2016

Figure 5.4(j): Demonstration PSA location and non-PSA/non-deforested random point in January 2017

Figure 5.4(k): Demonstration PSA location and non-PSA/non-deforested random point in February 2017

Figure 5.4(l): Demonstration PSA location and non-PSA/non-deforested random point in January 2018

Figure 5.4(m): Demonstration PSA location and non-PSA/non-deforested random point in December 2018

Meanwhile, the nearby non-PSA non-deforested point appears to be in a parcel of land that has seen varying amounts of structures built on it, starting with a building to its west in February 2004, which seems to have been taken down later. Then, sometime between February 2014 and November 2016, a new area was cleared for a new set of buildings, and the point now looks to be barely in their backyard.

Whether it is in their backyard or not seems like an insignificant consideration in the broader picture, but this highlights a quirks of the methodology here: it may depend on apparent "hairline" inaccuracies between Google Earth imagery and its map features, which can be easily seen from the location of the nearby road when comparing imagery to Google Earth's road feature markings (relative to which the provided coordinates are fixed). Either this needs to be corrected, or it may be better to look at a land parcel as a whole, using the points to identify the parcels themselves for analysis, rather than focusing at the exact conditions at a given point. However, this idea complicates the forest/no-forest or deforested/not-deforested binary distinction that makes for a simple comparison.

The inconsistency of Google Earth's time series is also on display here, as imagery is irregularly captured. Some years there are multiple images; other years are missing images entirely, which hampers its ability to pinpoint exactly when any instance of forest clearing began. Images are not captured evenly across the seasons; this hampers their ability to display phenology. Furthermore, as mentioned earlier, multiple images are mosaics, calling into question the accuracy of the provided imagery date. Despite these drawbacks, Google Earth imagery manages to provide an informative look into the land cover history of these two locations.

Figure 5.5(a): Non-PSA deforested (in 2015) random point in March 2004

Figure 5.5(b): Non-PSA deforested (in 2015) random point in September 2009

Figure 5.5(c): Non-PSA deforested (in 2015) random point in December 2011

Figure 5.5(d): Non-PSA deforested (in 2015) random point in September 2015

Figure 5.5(e): Non-PSA deforested (in 2015) random point in February 2017

Figure 5.5(f): Non-PSA deforested (in 2015) random point in February 2018

Figure 5.5(g): Non-PSA deforested (in 2015) random point in December 2018

Figure 5.5(h): Non-PSA deforested (in 2015) random point in January 2020

The time series for the non-PSA deforested point is presented in Fig. 5.5; forest loss was recorded here in 2015. Again, dry forest phenology is suggested by the deforested look in March 2004 compared to the forested look in September 2009. The imagery here is even more sparse in temporal coverage, with two timepoints actually displaying duplicated imagery from an adjacent timepoint – Fig. 5.5(b), timestamped September 2009, is followed by an identical image (not shown here) timestamped October 2010; the same duplication happens to Fig. 5.5(c), timestamped December 2011, which was duplicated for an image timestamped February 2014. A building was present east of the point in December 2011, but was taken down by September 2015, though there was also more land cleared then. While subsequent imagery is not perfectly clear as to whether this point was itself deforested, the loss year data supports the idea that there was forest loss here in 2015, as the vicinity appears to remain partly cleared in later images.

The results in Fig. 5.4 can be compared to the location of the deforested pixel in the PSA polygon, shown in Fig 5.6. As noted earlier, there may have been deforestation as early as May 2013, but its location in the polygon does not seem to match the 2013 loss year pixel shown in Fig. 5.4, and appears to be a false positive after other areas have been cleared, while other pixels appear to be false negatives since they do not report the clearing near the northern edge of the parcel. However, if these geographic data are not properly aligned, that loss year 2013 pixel may yet accurately reflect forest loss. This highlights the usefulness of checking in detail, but also underscores the uncertainty of relying solely of on forest loss year data.

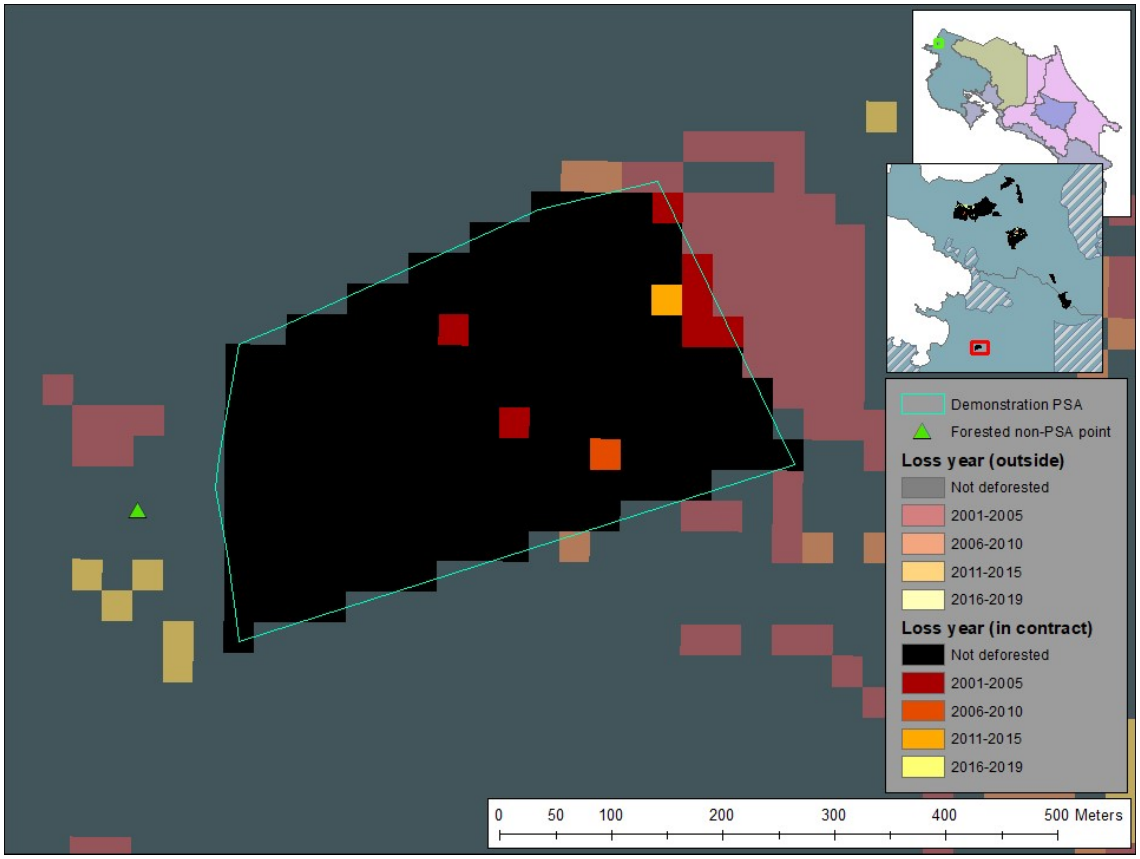

Figure 5.6: Detailed map of forest loss raster pixels in selected PSA area and nearby non-deforested random point

5.5 Further remarks

In summary, this closer examination of PSA and non-PSA locations has revealed a number of details that are otherwise not visible in the analyses of chapters 3 and 4.

The regional analysis shows that the region's distribution of forest loss year pixels and its estimated deforestation rates differ from those of the country as a whole, for comparably-selected contracts. A larger data pool, covering a larger geographic area (such as an entire province) other category, would make for more meaningful contract count comparisons and single contract-year estimates of deforestation. Obvious categorizations include Holdridge life zones and administrative subdivisions (such as provinces), though PSA contracts can cross their borders so it would be important to clarify the criteria for selection.

For doing a proper comparison, deforested points located closer to the PSA polygon (which are present, as shown in Fig. 5.6) might be more appropriate, which shows the distance between the deforested point chosen here (pink triangle) and the presence of much closer points (reddish pixels) that were deforested in 2011-2019. A new sample of randomly-selected points, at a higher average density, may address this.

The process shown here is informative and can be repeated but is labor-intensive. Perhaps automating this might be possible with the help of artificial intelligence, but that is far beyond the scope of this paper.

The FONAFIFO 2020 dataset does not contain PSA contract polygon maps for recent years; instead it represents PSA contracts by single points. This can still be used to find closest non-PSA points for comparison, but without information on the contracted area, it would not be possible to examine PSA performance.

Further discussion on this and the other analyses follows, in Chapter 6.

CHAPTER 6: CONCLUSIONS AND DISCUSSION

6.1 Summary of and commentary on results

The past three chapters (Chapters 3, 4, and 5) have made use of a few different approaches to evaluating the effectiveness of Costa Rica's *Pago de Servicios Ambientales* (PSA) program, a program that offers payments for ecosystem services (also known as payments for environmental services, abbreviated PES). As explained in chapter 1, PES programs are meant, at least in principle, to compensate landowners for the "ecosystem services" their land provides. The legal underpinnings of Costa Rica's PSA, which have been in place since 1997, identify carbon sequestration, groundwater resources, biodiversity conversation, and scenic beauty as the "environmental services" provided by forests, as justification for a legal mechanism for protecting them (in addition to other activities such as reforestation). Chapter 2 then examined a variety of papers in the literature, from both peer-reviewed and non-peer-reviewed sources, that have attempted to evaluate the effectiveness of PSA in various ways. Chapter 3 picked a random selection of points outside of PSA contracts (and outside of protected areas), in order to estimate the deforestation rate in the absence of PSA. Chapter 4 looked into PSA protection contracts themselves, assessing the occurrence of forest loss pixels at the level of individual contracts and the pixels they cover. Finally, while both Chapters 3 and 4 cover country-wide surveys, Chapter 5 presents a detailed look at a subset of PSA contracts, applying the same method to them as in Chapter 4, and showing how they differ from the country-wide result; one specific PSA protection contract and two non-PSA points near it were examined to demonstrate the use (and limits of) publicly-available Google Earth imagery to understand the change in forest conditions over time in a given location. These chapters also detail their methodology, and it is hoped that these procedures, imperfect though it may be (as they are limited by its data sources and toolsets), may be useful for future studies of Costa Rica's PSA, and perhaps even PES programs in other countries. In summary, this dissertation presents the methods and results of an estimation of the effectiveness of the PSA program.

Since prior studies of PSA have covered time periods before 2010, this study examines PSA and forest loss beyond 2010. The results from Chapters 3 and 4 suggest that, in recent years, Costa Rica has continued to see a low rate of gross forest loss, which the PSA appears to further reduce. Calculations from Chapter 3 produced estimates of non-PSA gross deforestation rates in a range from 0.320% to 0.403% loss per year. Compared to the following studies analyzing the period 2000-2005, the results here are slightly smaller than those of Robalino et al. (2011) (0.50% to 0.69%, depending on method and sub-period 2000-2002 vs. 2003-2005) and comparable to the results of Robalino et al. (2008) (0.28% to 0.42%, depending on method).

In both those studies, methods that did not use matching techniques reported lower estimates (0.50% in the former, 0.28% to 0.32% in the latter) of avoided deforestation, compared to those that did (0.61% to 0.69% in the former, 0.33% to 0.46%

in the latter). This result would be consistent with effective targeting of PSA, because that means PSA-comparable locations had higher deforestation rates to reduce, than did locations in general (in "raw" comparisons). Since Chapter 3 in the present dissertation did not use matching techniques or even ordinary least squares, and so it basically is a "raw" comparison, albeit specifically using gross deforestation. If PSA targeting has not become less effective since the timeframes of those studies – and Porras et al. (2013) report that targeting efforts have seen further improvements since 2010 – the actual deforestation rate prevented by PSA is likely higher. Thus, the results from Chapter 3 can serve as a backdrop for comparison for future studies of this time period that do use more rigorous econometric methods.

Meanwhile, Chapter 4 found that rate of forest loss pixels was further reduced in PSA polygons. A direct comparison from a specific time period 2011 contracts from 2011-2015 vs. non-PSA areas from 2011-2015) showed that this rate of gross forest loss was found to be 0.101% lower in PSA polygons than in non-PSA areas. More generally, as shown in Figs. 4.3 and 4.5, typically about 0.1% to 0.2% of the pixels in PSA polygons themselves reported gross deforestation. PSA polygons are not the same as PSA contracts, but if we assume that they are, then, in comparison to Chapter 3's results (temporarily putting aside the methodological differences and other caveats), that would suggest a net reduction in gross deforestation comparable to this figure.

Chapter 5 does not provide any broad-scale conclusions about the whole country, as it only examines three specific locations. However, its purpose was to exhibit the presence of regional variability in the effectiveness of PSA, and to demonstrate the use of imagery from Google Earth in revealing the details of locations over time. While the number of PSA contracts chosen was small, the methodology from Chapter 4 was able to find a comparable, but different result – a direct 2011-2015 comparison using 2011 contract pixels only found a reduction in gross deforestation rate of 0.081%. As for Google Earth imagery, despite its temporal irregularity, it served as a time series that (1) checked the accuracy of the gross forest loss year data, (2) revealed details within the spatial extent of an individual PSA contract, including what may be deforestation occurring *after* the term of a contract, and (3) revealed some details of the phenology of the dry forest life zone. Furthermore, by examining this contract individually, it was revealed that this particular contract was the sole contract from 2011 that might not have a properly-recorded contract size (in the PSA dataset provided by FONAFIFO).

Overall, this work presents a snapshot into the recent effectiveness of the PSA program, by comparing non-PSA locations and PSA contracts. Of course, this work is not without its limits and caveats, and which are further discussed below.

6.2 Caveats and other discussion

This work is neither flawless nor comprehensive; the methodology used here could be improved and supplemented in a variety of ways. The following discussion of caveats – factors that were not properly accounted for or considered – is sorted by topical relevance, first discussing caveats that apply generally, then caveats pertaining to data sources, then chapter-specific caveats.

6.2.1 General methodology discussion

First, the idea of evaluating Costa Rica's PSA program for its additionality may not truly reflect the PSA concept. The whole idea of trying to isolate the effect of PSA aims to answer a question of how "additional" its effects are, compared to the absence of it. However, Costa Rican law defines the ecosystem services provided by forests, and PSA exists (at least in principle) as a program to compensate resources owners for these services; this is in contrast to the idea of incentive programs, which – though similar, and the predecessors of PSA itself (as described in Chapter 1) – can be seen as temporary measures towards an end. An "incentive" might not be needed once a certain practice is sufficiently common; a "service" however deserves payment whenever rendered. Even the terms "payments for ecosystem services" and "*pago de servicios ambientales*" explicitly state the idea that these are "services". Such services do not stop being rendered because there is no more deforestation to prevent; the justification of PSA arguably remains even if it has no additionality.

Second, the effectiveness of Costa Rica's PSA alone can't truly be evaluated, because of the concurrent ban on soil use/forest clearing (as mentioned in Chapter 1, with reference to the relevant law and to papers such as Daniels et al. 2010 and Fagan et al. 2013). This applies to any study of Costa Rica's PSA. However, this general approach may be able to isolate the effect of a payments for ecosystem services (PES) system in a country where a PES system does not coincide with such a bans on land use change.

The deforestation ban is not the only factor specific to Costa Rica. The country's strong international reputation as an ecotourism destination contributes to its economic activity, the economic value of ecosystem conservation efforts, and the idea that its forests provide ecosystem services (of the legally-defined categories, scenic beauty and biodiversity are most relevant). Would PES programs be less successful in countries with less ecotourism activity, or would they have more impact due to not "duplicating" other strong environmental traditions and policies as they might in Costa Rica? That is a question that would have to be explored separately, the terms and implementation of PES programs may be tailored to their specific territories, making direct comparisons difficult. Furthermore, the downturn in travel due to COVID-19 may have effects on ecotourism not explored here; see comment in section 6.3 regarding this.

This dissertation also does not measure the effectiveness of PSA in educating the public (suggested in Sills et al. 2008) or otherwise changing attitudes toward a deforestation ban in order to incentivize compliance (suggested in Sánchez-Azofeifa et al. 2007, Pagiola 2008, Pfaff et al. 2008, Daniels et al. 2010). The educational effects would most simply be observed by interviewing landowners and their peers, though there may be other methods to tease out the effects of raising awareness.

Also, public lands were not properly excluded when taking a random sample of relevant non-PSA points. PSA is meant to target privately-owned lands, so a properly representative non-PSA sample should exclude public lands. While the locations of PSA contracts, protected areas, and non-forested points in 2010 were excluded, relevant GIS data was not available for public or private land ownership, so the public/private split was ignored. The effect of this lack of exclusion could go either way, depending on the land use of public lands.

In a similar vein, nothing was done to account for the possibility of land changing from public to private (or vice versa), or changing its protection status.

Finally, no ground-truthing was done here. The use of detailed manual analysis of aerial photographs provided by Google Earth, demonstrated in Chapter 5, can substitute for ground-truthing to some extent, since its spatial resolution (at least in the part of Costa Rica examined) is sufficient to determine land cover conditions – some trees can even be distinguished individually. A resource such as Google Earth imagery can reveal more than do simple measures of forest cover or forest loss, such as those used in Chapters 3 and 4, providing a more nuanced picture of the actual forest cover. However, this coverage was not expanded because it is labor-intensive and cannot be scaled up efficiently, except with resources not currently available to this project, such as automation. Furthermore, satellite and aerial imagery can never fully substitute for in-person ground-truthing; it is unable to fully discern such factors as forest thinning and tree species biodiversity, both of which relevant to the legally-defined ecosystem services. Lastly, Google Earth imagery does not form a consistent, regular time series, so it is not ideal for a rigorous analysis requiring a time series. That said, this option may be somewhat more attractive when travel is difficult, such as during the current pandemic.

Along with lack of ground truthing, the present work did not interview landowners. While this can reveal important information on land condition, land use history, landowner intentions, and opinions on the PSA program, it may be even more labor-intensive than ground-truthing. Information this might reveal includes the financial/economic situations faced by landowners, their land use decision-making process, and their awareness of ecosystem services and PSA (as mentioned earlier).

6.2.2 Discussion regarding data sources

Regarding maps of forest cover and forest loss, the usual understanding that they depend on interpretation of remote sensing imagery (and thus may not be fully accurate) is generally applicable – hence the importance of ground-truthing. In addition, the following factors apply to the datasets used here.

Forest cover data was acquired for 2010 (the "Global 2010 Tree Cover (30 m)" dataset), whereas forest loss year data started counting forest loss from 2001 (the "Global Forest Change" dataset). They were produced by the same research center and likely share methodology, though the measures are ultimately derived differently.

Forest cover in 2010 is a binary measure, defined as 51% or more tree cover using the whole-number percent tree cover in the dataset. While it was used in Hansen et al. (2013) (described in its supplementary materials as ">50% crown cover to ~0% crown cover", this is still ultimately an arbitrary distinction, since forest cover is a continuum.

A curious "banding" pattern, illustrated in Fig. 6.1, was observed for loss year data from 2011, 2012, and 2013. This type of pattern seems absent from, or at least less apparent in, loss year data from 2014 onward, based on a (non-rigorous) manual examination. (This banding pattern is only apparent at this resolution if the raster is first converted to polygon format, because if displayed in raster format, ArcMap does not display some loss year pixels.)

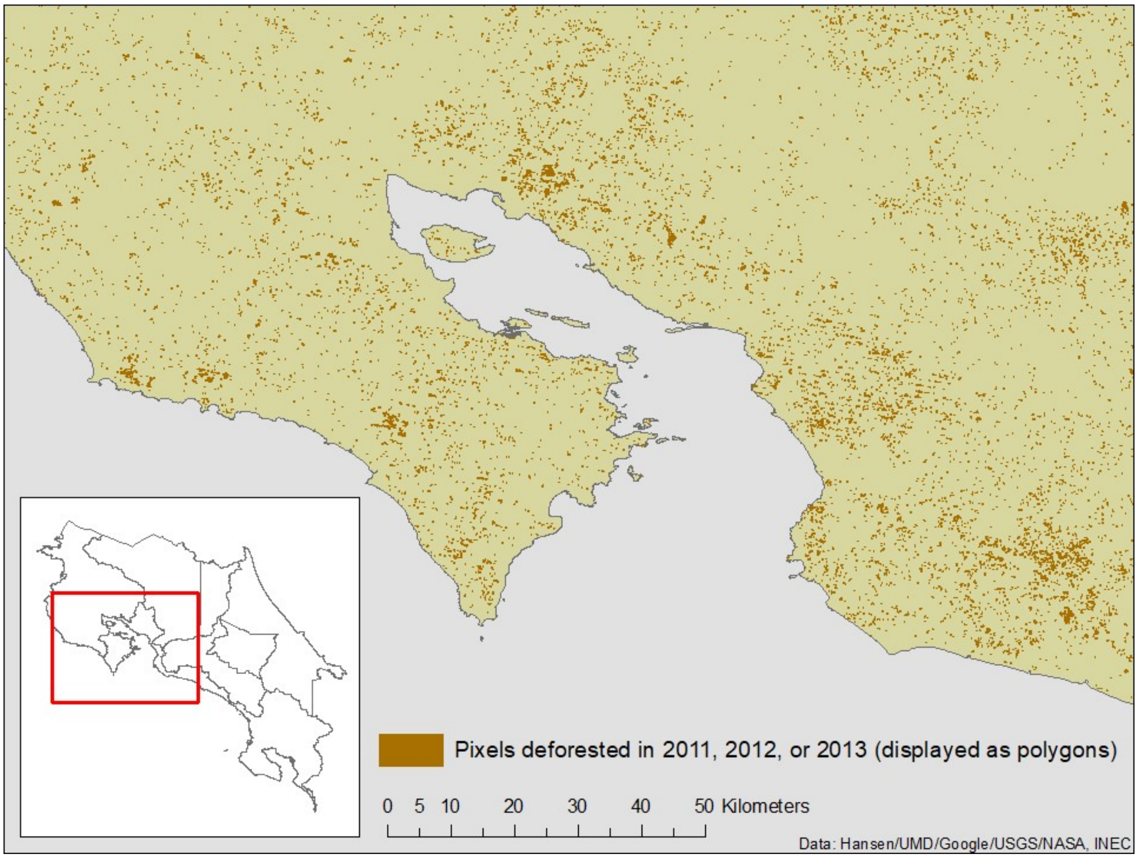

Figure 6.1: Map showing distribution of 2011-2013 forest loss year pixels

Forest loss year data measured gross deforestation, i.e. only counting instances of forest loss, and not forest gain/regrowth. Accurate assessments of some ecosystem services, such as biological carbon sequestration, would be better served using measures of net deforestation. (Gross deforestation may still be useful in some respects, such as distinguishing between primary and secondary forest, which may be a related to biodiversity.) Similarly, the forest loss dataset may lack a fuller picture of the permanence of forest loss: each pixel was either never deforested since 2000 or has a single forest loss year associated with it, so it is possible for a pixel to represent a location that was deforested, reforested, then deforested again, but this would only recorded as one deforestation event.

The alternate forest cover dataset provided by CEOS at the University of Alberta, which covers 2010-2013, would have provided proper before-and-after forest snapshots of forest cover, thereby avoiding the question of permanency of forest loss. It is also more specifically tailored for Costa Rica than the global dataset provided by GLAD, and thus it may have better accuracy. Unfortunately, ArcMap did not have a conversion from its coordinate system to the coordinate systems of other datasets used here, and the geolocation error that it introduced was deemed too significant. An examination of this error, and an analysis using it in the procedure of chapter 3, are in Appendix A.

Other data sources generally used a combination of the following coordinate systems:

- CRTM05 (Costa Rica Transverse Mercator 2005), a projected coordinate system which was used as the “official” coordinate system in this dissertation.
- CR05, a geographic coordinate system, and a Costa-Rica-specific datum that forms the basis for CRTM05. No conversion was used between CR05 and CRTM05.

- WGS 1984, a geographic coordinate system made from an older datum. A built-in conversion in ArcGIS (named "CR05_To_WGS_1094_1") was used to convert from this to CRTM05.

Even though a conversion was used, some hairline inaccuracies remained, though to a much lesser extent than the aforementioned error (see Fig. A.2 for an illustration).

As for the data on PSA contracts themselves, there were two FONAFIFO datasets, from 2018 and 2020. They both had the same 2011-2014 PSA polygon data, but the 2020 dataset replaced PSA polygon data from 2015-2018 with point shapefiles. Comparing the number of contracts in the latter period showed that there may be contracts missing from the 2015-2018 PSA polygon data especially 2018), as detailed in section 3.2.1. Unfortunately, point shapefiles were not directly usable for the analysis here (though they may be usable if a map of private properties were available), so they were ignored aside from noting this caveat. (The varying numbers of PSA protection contracts per year led to the step in Chapter 4 of standardizing the results by dividing by the total number of contracts or pixels in a given year.)

Data was not available on PSA contracts from 2010 and earlier. Contracts last multiple years, and thus efforts to exclude PSA locations from analysis (such as in Chapter 3) did not exclude areas in earlier contracts.

A few protection contracts were excluded from the analysis in Chapter 4 because of data format errors, likely due the attribute table improperly handling letters with diacritics, which is what caused sub-modalities to be indistinguishable for some years, as mentioned in section 4.2.

As detailed in chapters 4 and 5, PSA protection contracts do not necessarily have the same number of hectares under contract (according to their attribute data) as the size of their polygon on the map. In many cases, the two figures are relatively close, but in other cases, the polygon size can be vastly larger than the hectares contracted. There was no information available to indicate what part of that polygon area is under contract, so the whole area was included in Chapter 4 for within-PSA analysis.

The contract data may have other errors. For example, Chapter 5 took a closer look at the PSA contracts and found a 2011 protection contract with 0 hectares under contract.

As for ancillary data provided by INEC, road networks did not have properly defined coordinate systems and thus were excluded from Table 5.2. Elevation data also showed geolocation errors in the contour lines map from INEC, but the data points examined in Chapter 5 were conveniently located such that their elevation range was clear nonetheless.

The limitations of Google Earth imagery are documented in section 5.4, and further discussed in subsection 6.2.3.

6.2.3 Chapter-specific discussion

Chapter 3 attempted to estimate (gross) deforestation rate in non-PSA locations, in order to determine the amount of avoided deforestation. As explained in section 6.1, only a "raw" comparison was performed; matching techniques like covariate matching and propensity score matching were not used (contrast Robalino et al. 2008, Robalino et al. 2011). A more rigorous estimate of avoided deforestation could use such techniques.

Also, as mentioned in the caveats on data sources, the procedure of Chapter 3 excludes neither points that were in prior years' PSA contracts that had not yet expired, nor points that were on public lands.

As mentioned in Section 4.5, the approaches of counting pixels and counting contracts are not fully comparable. Counting pixels allows us to analyze the extent of area coverage of PSA, which would be useful for determining its contribution to carbon sequestration, for example. However, counting contracts may reveal other information, such as differences in the performance of smaller vs. larger contracts; this was not explored in the present work.

The procedure demonstrated in Chapter 5 provides useful information that can be used to create a customized assessment of individual contracts, but is labor-intensive relative to the amount of spatial coverage and hard to scale up. Perhaps it could be automated using artificial intelligence tools, but those are far beyond the scope of this paper. Still, the easy access to Google Earth imagery means that it remains a useful tool for doing a quick check on any location, including any PSA parcel if its location is known. (PSA data would have to be requested from FONAFIFO or a landowner.)

As mentioned earlier, Google Earth imagery does not present a full, regularly-sampled time series, the way other resources do (e.g. Landsat imagery). Google Earth seems to provide roughly one image a year, but at varying times of year, and inconsistently skips years. This limits it to being more appropriate for verifying changes in forest cover indicated by another data source, rather than monitoring forest condition consistently.

The timing of Google Earth imagery may also obscure some aspects of the phenology. The demonstration in Chapter 5 chose an area known to have dry forest, because it has historically been more difficult to assess properly (Kleinn et al. 2002). Google Earth imagery in the two demonstration locations (see the time series in Figs. 5.4 and 5.5) were mostly from September through February, commonly December and January, likely due to avoidance of cloud cover, as these times correspond roughly to the dry season (roughly November through May). One image from May (late in the dry season) exhibits a seemingly deforested look, and is the best display of phenology from among the images available.

The spatial resolution of Google Earth imagery also varies between locations, meaning that the detail revealed can vary in turn. The locations examined in Chapter 5 are fortunate enough to have reasonably high-resolution aerial or satellite imagery from which forest cover can be observed, but this dissertation did not verify the availability of such resolution over the entire country. Furthermore, some locations have street view, which can further enhance this resource's ability to verify forest cover, though much of Costa Rica does not have street view, and where street view is present, high-resolution remote sensing imagery is likely already available, based on this author's experience.

Finally, as mentioned above, public lands were not properly excluded. Thus, the two non-PSA comparison points used in Chapter 5's demonstration were not confirmed to be on private property. (This could be verified by consulting property records from the Costa Rican government.)

6.3 Ideas for further research

Any work that expands our understanding of Costa Rica's PSA, or PES programs in general, is welcome, including work addressing the caveats and imperfections mentioned above. This section makes special mention of some of them.

One obvious idea is to fully replicate the analysis using matching techniques done in prior research, such as Robalino et al. (2011), but for years beyond their original scope (i.e. beyond 2005). This would enable the best apples-to-apples comparison over time with past performance of PSA. PSA targeting efforts have changed over the years (Porras et al. 2013, as summarized here in Chapter 1, section 1.4), so a rigorous before-and-after comparison might reveal the benefits, if any, of such improvements. (The attribute table in Chapter 5, Table 5.2, pays homage to this sort of econometric analysis, by examining the ancillary data associated with PSA and non-PSA locations.)

Some studies comparing PES programs in different countries already exist, such as Pattanayak et al. (2010), and further work in this direction may be able to use Costa Rica's experience with PSA to improve it and other PES programs by understanding their interactions with different ecosystems, people, economies, and legal systems.

The detailed analysis using Google Earth imagery demonstrated in Chapter 5 can be replicated for other locations, so it may to see to what extent it can be automated through artificial intelligence, and/or crowdsourced through efforts like those of OpenStreetMap, particularly its “map-a-thons” events, wherein large numbers of people gather to interpret remote sensing imagery into map features.

The work here can be expanded to produce an estimate of carbon sequestration. Carbon stock inventory overall can be estimated by overlaying a life zone map (such as Bolaños et al. 2005) on a map of forest cover, and then applying estimates of carbon density per hectare (such as those found in Tattenbach et al. 2007) based on life zone. Similarly, an estimate of the amount of avoided deforestation in an area the size of the coverage of PSA protection contracts can be multiplied by the carbon density in the life zone corresponding to the location of each PSA protection contract, to arrive at an estimate (at the life zone level) of the carbon sequestration value of the PSA program. This would estimate both the impacts of PSA forest protection on mitigating climate change and quantifying the legally-defined ecosystem service of carbon sequestration.

Furthermore, because PSA protection contracts are paid on a per-hectare basis, this can be converted into a de facto price per ton of carbon sequestered per year: for example, in 2011, a forest protection contract paid US$320 per hectare, split evenly over 5 annual payments (FONAFIFO 2018a). (Contract payment amounts were formerly given in US dollars, but later switched to Costa Rican colones.) Tropical wet forest (“bosque muy húmedo tropical”) contains 88 tons of carbon per hectare (tC/ha), according to Tattenbach et al. 2007 (which references a MINAE document for carbon densities). Dividing this payment amount by the carbon density, we arrive at the price of about US$3.64 per ton of carbon sequestered for five years, or about US$0.73 per ton of carbon sequestered per year. Obviously, this calculation is very tentative, and a more rigorous analysis would require further research that is of great interest but is outside the scope of this dissertation.

Finally, the ongoing COVID-19 pandemic has caused a severe downturn in the amount of travel, globally. The effects of the pandemic on ecotourism, on funding for PSA, and on its ability to deter deforestation are not yet clear, but they are very relevant to the continued viability and effectiveness of the PSA program. There may be short-term effects, some of which may be delayed, affecting the finances of individual landowners whose land use decisions may be influenced by payments, as well as long-term effects wherein the program may be restructured and its funding sources reconsidered. These aspects are not part of the present research and would need (and ought!) to be explored in a separate effort.

APPENDIX A: NON-PSA DEFORESTATION ANALYSIS WITH AN ALTERNATIVE DATASET

The procedure described in section 3.3 was originally performed using forest cover data from the Centre for Earth Observation Sciences (CEOS) at the University of Alberta.

This research center produced forest cover maps of the country dated to 1997, 2000, 2005, 2010, and 2013, in cooperation with government agencies in Costa Rica, including FONAFIFO, which runs the PSA program. Reports covering these forest assessments can be found in the references EOSL 2002 (the 1997-2000 forest assessment report), FONAFIFO 2007 (the 2003-2005 forest assessment report), and FONAFIFO 2012 (the 2009-2010 forest assessment report).

These forest cover maps are specific to the country of Costa Rica, and have the potential to be higher-accuracy datasets than what GLAD provides on a global basis. Also, these forest cover maps can show *net* forest cover gain/loss, as opposed to Global Forest Change data (Hansen 2013) which only shows *gross* forest loss. This could have provided us with a more accurate/comprehensive picture of the change in forest cover.

Furthermore, CEOS forest cover data was already classified into forest vs. non-forest (and no-data) categories, obviating the step of choosing a >50% tree canopy cover threshold to determine forest cover when using GLAD data. Obviously, the presence of forest is still not really a binary distinction, even though it must be reduced to such for this analysis.

Unfortunately, I was unable to properly align CEOS data with the rest of the data sources used, so the results of the analysis using CEOS data are described here in this appendix, along with illustrations of the geographic alignment issues encountered.

A.1 Coordinate system information and alignment check

As mentioned in Chapter 3, CEOS data use a coordinate system identified as "165_Lambert_Conformal_Conic", whose projection is nearly identical to the "Costa Rica Lambert Norte" projection (a.k.a. "Costa Rica Norte", an older projection centered on the northern part of the country, but used by CEOS data for the entire country), but with the WGS 1960 spheroid instead of the Clarke 1866 spheroid (which is used in Costa Rica Lambert Norte). The ArcGIS coordinate system information for this dataset is as follows:

165_Lambert_Conformal_Conic
Authority: Custom

Projection: Lambert_Conformal_Conic
false_easting: 500000.0
false_northing: 271820.522
central_meridian: -84.33333333
standard_parallel_1: 9.999999996666666
standard_parallel_2: 11.0
latitude_of_origin: 10.46666667
Linear Unit: Meter (1.0)

Geographic Coordinate System: GCS_165
Angular Unit: Degree (0.0174532925199433)

Prime Meridian: Greenwich (0.0)
Datum: D_165
  Spheroid: 165
    Semimajor Axis: 6378165.0
    Semiminor Axis: 6356783.0
    Inverse Flattening: 298.2959966326797

Unfortunately, ArcMap did not provide a way to convert this coordinate system to the other datasets, which make use of the WGS1984 and CR05 datums. This resulted in a conspicuous misalignment of geographic data. The extent of misalignment was explored, and is illustrated in Figure A.1, a close-up of the area around the Cabo Blanco Absolute Natural Reserve. (This picture uses the polygon version of the CEOS forest cover shapefile, converted from the raster original as described in the next section.) This mis-alignment was greatly decreased when using GLAD 30m data for forest cover, shown in Fig. A.2 for comparison. Also compare the image of the same area from Google Earth, for reference, in Fig. A.3.

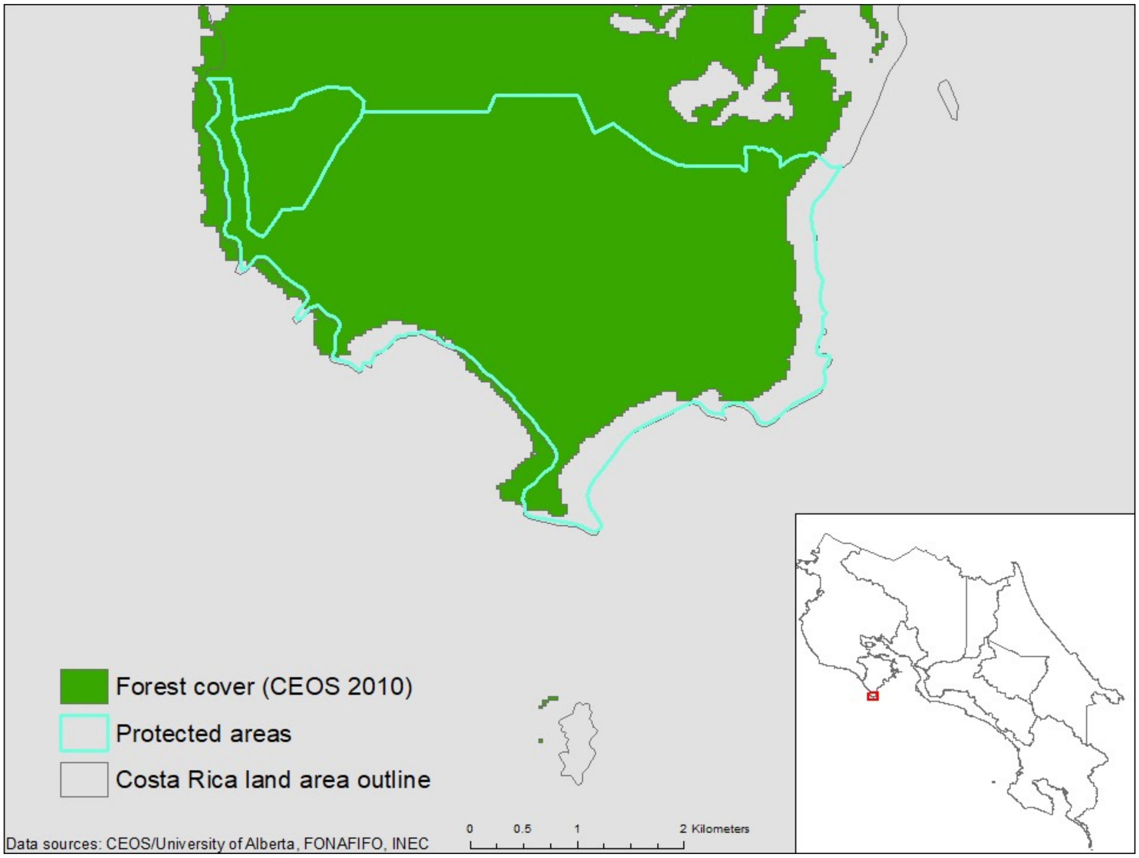

Figure A.1: Map of Cabo Blanco area with geographic mismatch

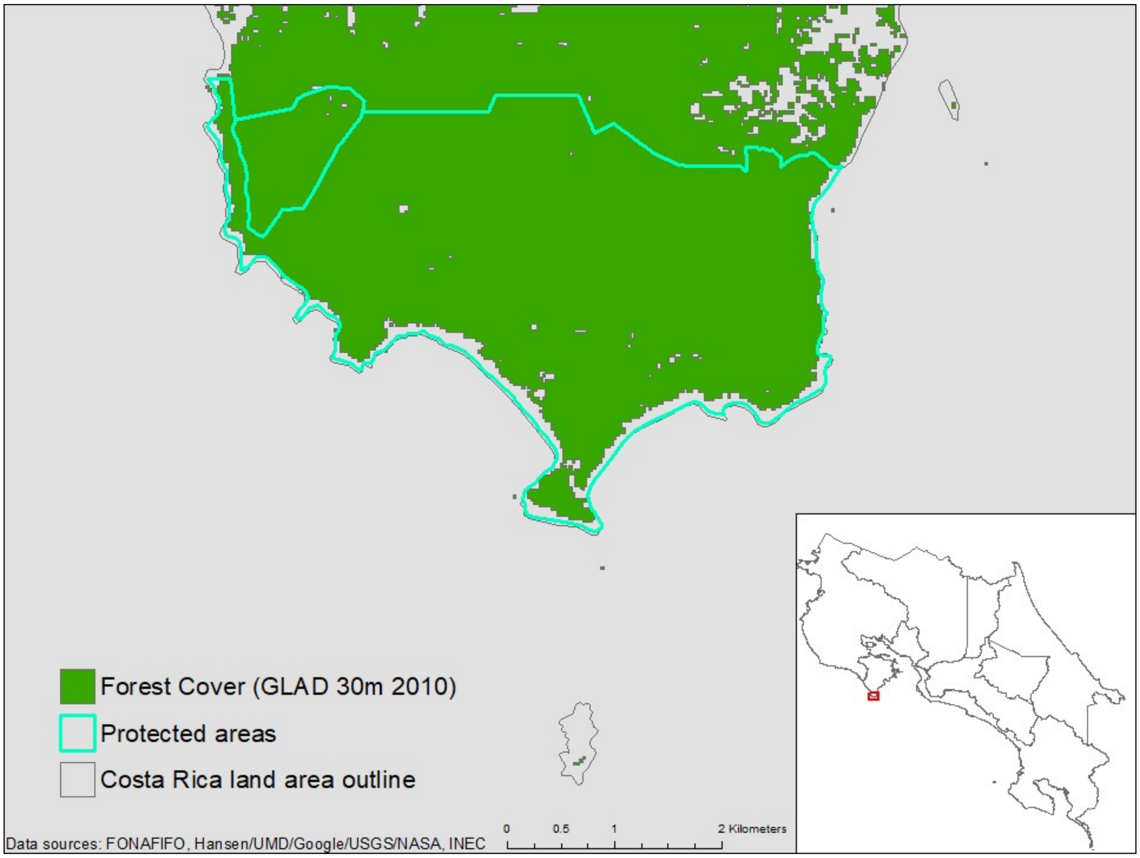

Figure A.2: Map of Cabo Blanco area using dataset with less mismatch

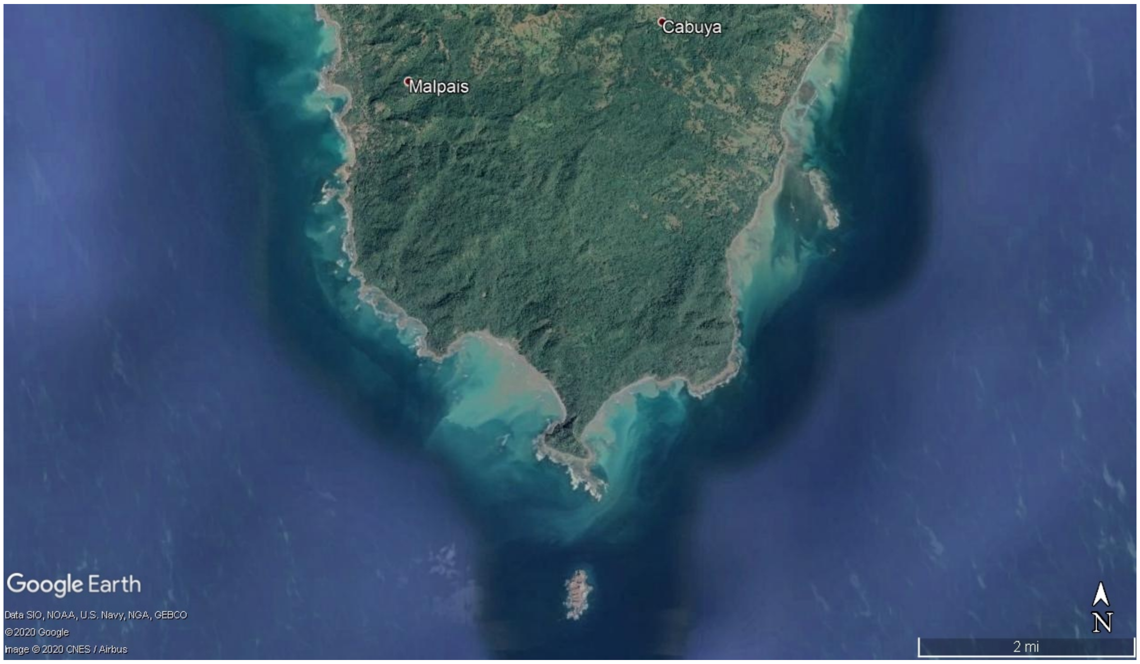

Figure A.3: Cabo Blanco area in Google Earth, for reference

The misalignment of the CEOS dataset relative to the others – of more than approximately 300 meters, based on a measurement inside ArcMap – was deemed too significant and thus the decision was made to seek a different data source, leaving behind the potential benefits of this dataset. No dataset is expected to be perfect, and errors in the GLAD 30m dataset also happen to be visible in Fig. A.2 (in the form of pixels identified as "forest" that are actually beyond the coast), but for the bulk analysis of Chapter 3, this latter dataset was used.

A.2 Procedure

Broadly speaking, the same basic method as described in Chapter 3 section 3.3 was used. First, 50,000 random points were chosen across the country, as described there. The same random starting sample of 50,000 points was used.

Second, non-forest points were then excluded, but instead of using GLAD 30m data to determine which points were forested, data from CEOS's 2010 forest cover map was used. Like the GLAD 30m dataset, the CEOS dataset was converted to a polygon format for use with selection features in ArcMap; in this regard, the CEOS forest cover map was of more manageable size, even in polygon format, so no mosaicking was needed. Furthermore no Costa Rica country mask was needed as this dataset was already bounded by the extent of the country. After excluding non-forest, 25554 points remained.

Third, inapplicable points were excluded. Because CEOS forest cover maps were only available for 1997, 2000, 2005, 2010, and 2013, and FONAFIFO PSA contract data were available for years 2011-2018, the only timeframe for analysis was 2010-2013. To exclude protected areas, the FONAFIFO 2018 dataset's version of the protected areas map was used. Again, it was assumed that no protected areas had been degazetted, so that the map of protected areas as of 2018 would be applicable to the 2010-2013 time period. To exclude areas enrolled in PSA, polygon shapefile maps of PSA contracts from 2011-2013 were used. After excluding protected areas, 15225 points remained; after excluding 2011 contracts, 14644; after excluding 2012 contracts, 14132; after excluding

2013, 13669. These points – randomly-chosen points that did not participate in PSA, were not part of protected areas in 2011, and had forest cover in 2010 – were compared against 2013 forest cover data from CEOS.

A.3 Results

Of these non-PSA (2011-2013) non-protected 13,669 points that were forested in 2010, 11,926 of them were still forested in 2013, while 1,743 became non-forest during 2011-2013. (None of the points became no-data.) Based solely on these numbers, and ignoring all caveats, this analysis suggests a 12.8% overall deforestation rate and an annual deforestation rate of 4.25%, calculated using equation 3.3 in Chapter 3.

A map of the locations of these points is shown in Fig. A.3 (compare Fig. 3.1; the same color scheme is used here). A curious geographical pattern appears: the (apparently) deforested points seem to be geographically clustered, which is not the expected result of a simple geographic misalignment. The northwestern cluster of these points seems to cover some of the tropical dry forests of Guanacaste, whose forest cover extent is known to be more difficult to assess than that of the moist forests and rainforests that characterize much of the rest of the country, so that might be a factor explaining the clustering.

Other caveats include those addressed in Chapters 3 and 6, such as pre-2011 PSA contracts not being accounted for and public lands not being excluded, as well as the fact that no further efforts had been made to look only at points similar (in geographic/geophysical characteristics) to existing PSA contracts. And of course, the coordinate systems were not properly aligned. However, any of these would have to be regionally-focused effects in those two areas, for them to explain the clustered pattern.

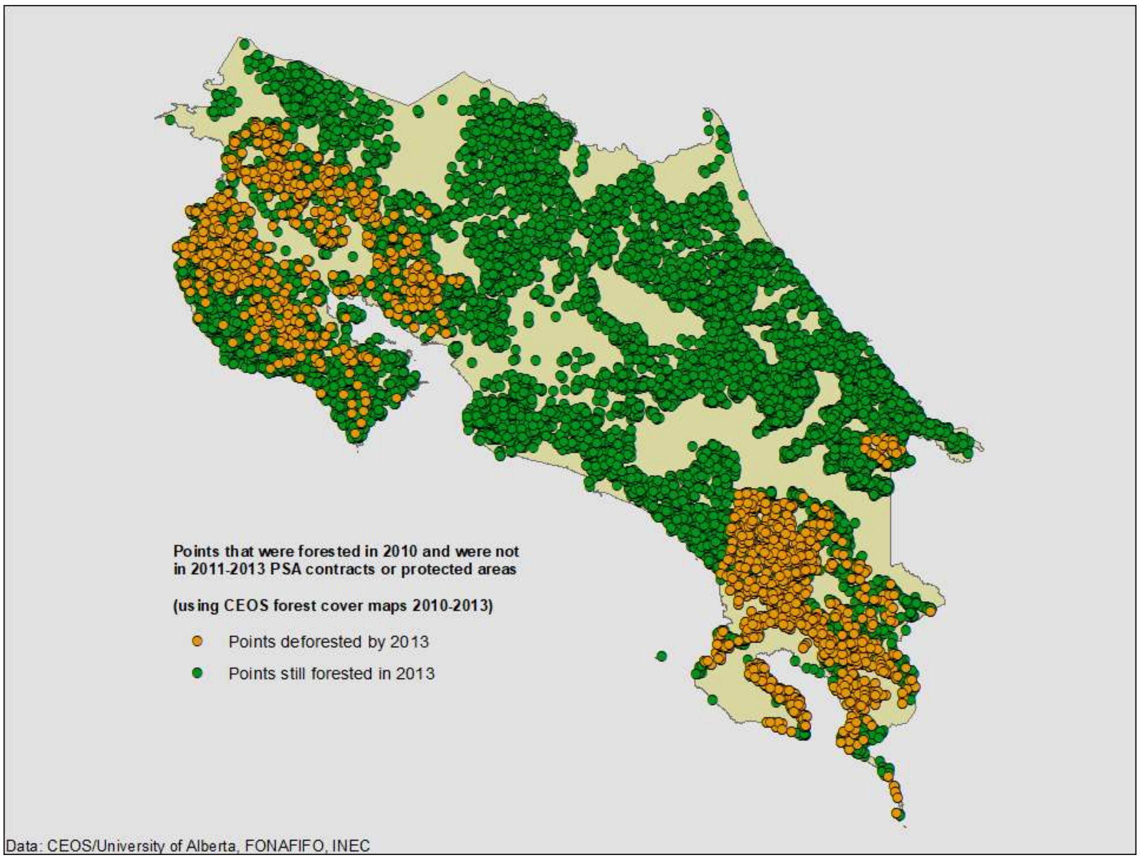

Figure A.4: Map of non-protected 2010 non-PSA (2011-2013) forest points deforested in 2011-2013 (alternative dataset)

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