IIIEE Theses 2023:35

Effectiveness of the Costa Rican Payments for Ecosystem Services program in mitigation of greenhouse gas emissions

Trends in carbon stocks 2012-2020

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Thesis for the fulfilment of the
Master of Science in Environmental Sciences, Policy & Management (MESPOM)
jointly operated by Lund University – University of Manchester -
University of the Aegean – Central European University

Lund, Sweden, June 2023

Erasmus Mundus Masters Course in Environmental Sciences, Policy and Management

MESPOM

This thesis is submitted in fulfilment of the Master of Science degree awarded as a result of successful completion of the Erasmus Mundus Masters course in Environmental Sciences, Policy and Management (MESPOM) jointly operated by the University of the Aegean (Greece), Central European University (Hungary), Lund University (Sweden) and the University of Manchester (United Kingdom).

Published in 2016 by IIIEE, Lund University, P.O. Box 196, S-221 00 LUND, Sweden,
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ISSN 1401-9191

Acknowledgements

I would like to thank my advisor, Dr. Naoko Tojo, for her constant support, valuable guidance, and continued interest in my topic. I am also grateful for her patience and thoughtfulness in providing direction.

I would also like to thank Dr. Themis Kontos for his generosity in sharing his expertise and time, he is a true gem in our program, and I have learned so much from him.

I am thankful to FONAFIFO and the REDD+ Secretariat in Costa Rica for providing the data that made my study possible. I am especially appreciative of Eduardo Mesén Solórzano from FONAFIFO for his time and. Additionally, I thank Rolando Castro Córdoba, Héctor Arce Benavides, and Adriana Aguilar Porras for providing key guidance and resources on my topic. I am grateful to all reviewers of drafts and versions of this study.

My family has been an unwavering support throughout all my academic career, and I owe every achievement to them. Thank you to Naomi for her constant understanding and my parents, Melody and Rodrigo, for their unconditional faith in me. I acknowledge so many family members for their example in my love of forests and commitment to conservation: my grandparents, Wolf and Lucky, my *tíos and tías*, and my parents.

My MESPOM classmates have been a constant source of support and joy in this program and getting to know them has been the part of this experience I will treasure the most. A special thank you to Renz for being my sounding board for many seemingly unconnected thoughts about payments for ecosystem services and for being my constant companion in this endeavor; *mahal kita*.

I am also incredibly grateful to the many people who provided support, encouragement, and resources to help me get here: Frank Joyce and Katy VanDusen, Dr. Wander Hernández, and many others. Thank you!

For my tío Carlos, the first in my family to go to graduate school. You flew on while I graduated, but you continue to inspire me. Every tree I plant, I'll think of you and your words:

"Plant every day. Regenerate the soils and ecosystems. Love all living beings."

Abstract

Payments for ecosystem services (PES), a mechanism of incentives or compensation to landowners for provision of ecosystem services, have grown as a tool for meeting conservation goals. The Costa Rican payments for ecosystem services (PSA) program is one of the best-known examples because of being one of the most established. Despite this, the PSA program and many other PES programs do not monitor the provision of ecosystem services directly, as they are not simple to measure and quantify and resources to systematically monitor them may not be available. This study uses maps of carbon stocks in Costa Rica, created based on REDD+ land cover maps and carbon densities, in conjunction with a database of almost 8,000 PSA program contracts for years 2012-2020, to explore trends in carbon stocks in the program. Each PSA program goal, priority area, and contract type explored in this study was associated with either higher carbon stocks or change in carbon stocks than the goals or baselines that they were being compared to. In spatial targeting, all priority areas were more carbon dense than non-priority areas, but protected areas, indigenous territories, and conservation importance were most effective at targeting areas of higher carbon density. In contract types, forest protection and forest management contracts had higher carbon densities at the beginning of the contracts than baselines, while agroforestry systems, reforestation, mixed systems, natural regeneration, and forest management contracts had higher rates of increase in carbon stocks than baselines. Scenarios that resulted in low carbon densities or growth rates may reflect tradeoffs with other ecosystem services or with other goals of the program. Assessment of other ecosystem services and program goals could help improve program design.

Keywords: Payments for ecosystem services, ecosystem services, carbon stocks, greenhouse gas emissions, mitigation

Executive Summary

Payments for ecosystem services (PES) are a relatively recent policy instrument used to provide incentives to land owners for the provision of a variety of ecosystem services. Although they have only existed since the 1990s, PES programs have grown to be widely used to meet conservation goals where traditional conservation mechanisms have failed. The Costa Rican payments for ecosystem services (PSA) program is one of the only long-term, national-level PES programs and is widely recognized for its achievements as one of the cornerstones of the country's environmental trajectory.

PES programs are frequently challenged in quantifying the ecosystem services that they provide incentives for, because it can be resource-intensive and difficult to measure the provision of many ecosystem services. The PSA program is not an exception and does not have a program for monitoring ecosystem service provision directly. In addition, evaluations of the effectiveness of the program have varied greatly in temporal and spatial scope, as well as methodologies. At the same time, the REDD+ Secretariat in Costa Rica has developed a consistent methodology for measuring changes in forest carbon stocks, emissions, and sequestration over time, providing data on one of the ecosystem services that the PSA program covers: GHG mitigation through carbon storage and sequestration. These data provide an opportunity to explore the relationship between PSA program design and management strategies and carbon stocks through the following questions:

1. To what extent are the goals set by the program on carbon storage and sequestration for climate change achieved?
2. Do spatial targeting and prioritization criteria prioritize areas with greater carbon stocks or carbon density?
3. Are certain contract types associated with higher carbon stocks or carbon density?

These elements of the PSA program design offer opportunities to influence the provision of ecosystem services. A time series of maps of carbon stocks in Costa Rica, created based on REDD+ land cover maps and carbon densities, in conjunction with a database of almost 8,000 PSA program contracts for years 2012-2020 were used to explore trends in carbon stocks in the program.

Each of the program design and management strategies explored in the research questions provided evidence of scenarios in which the PSA program was effective at delivering greenhouse gas emissions mitigation either through higher carbon stocks or growth in carbon stocks than baselines. A goal of 115 $MtCO_2e$ in active contracts per year was met and exceeded in 2019-2020, while prioritization areas did prioritize greater carbon stocks than non-priority areas. Regarding contract types, contracts for forest protection and forest management had higher carbon densities at the beginning of the contracts than landscape baselines, while agroforestry systems, reforestation, mixed systems, natural regeneration, and forest management contracts had higher rates of increase in carbon stocks than baselines.

Scenarios that resulted in low carbon densities or carbon stocks may reflect tradeoffs with other ecosystem services or with other goals of the program. Further research on carbon stocks and sequestration, in addition to data on all 4 ecosystem services and socioeconomic goals, would allow for better information for how to target relevant goals with management decisions.

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Abbreviations

ES	Ecosystem services
FONAFIFO	National Forestry Financing Fund
GHG	Greenhouse gas(es)
IFN	*Inventario Forestal Nacional* / National Forest Inventory
IPCC	Intergovernmental Panel on Climate Change
MINAE	Ministry of Environment and Energy
ONF	*Oficina Nacional Forestal* / National Forestry Office
PES	Payments for ecosystem services
PSA	*Pagos por Servicios Ambientales* / Payments for Environmental Services
REDD+	Reducing Emissions from Deforestation and Forest Degradation
SINAC	National System of Conservation Areas

1 Introduction

1.1. The multiple benefits of ecosystem services

Climate change is an increasingly important global threat, as it has had and will continue to have a profound effect on humans and the environment. While anthropogenic carbon emissions are one of the most important causes of climate change, terrestrial and marine ecosystems like forests, wetlands, or oceans are the greatest carbon sinks, storing organic and inorganic carbon in soils and sediments, biomass, and other compounds. Because ecosystems can store carbon, but also release carbon when they are degraded or destroyed, they can both decrease and increase the effect of climate change. Therefore, conservation and restoration of ecosystems can help mitigate the effects of climate change by increasing carbon sequestration and stocks. In fact, Bastin et al. (2019) estimated that there are 0.9 billion hectares of land that could be restored globally, which could store an additional 205 gigatons of carbon, the equivalent of about two thirds of the estimated anthropogenic carbon emissions to date (about 300 gigatons of carbon). Griscom et al. (2017) estimated that natural climate solutions, most of which are based on ecosystem restoration and management, could provide more than one third of the CO_2 mitigation needed before 2030 to stay in line with the Paris Agreement goal of holding warming to less than 2° C.

In addition to carbon sequestration and storage, forests provide many more important ecosystem services, which are the benefits that ecosystems provide people, including supporting services like nutrient cycling, provisioning services like food products, regulating services like water purification, and cultural services, such as aesthetic beauty (Science for Environment Policy, 2015). These and other benefits like protection of biodiversity can increase resilience of socio-ecological systems to changes, helping these systems to adapt to climate change.

For these and many other reasons, many nations have goals of protecting their natural ecosystems; for instance, over 100 countries support the 30x30 initiative, promoted by the High Ambition Coalition (HAC) for Nature and People, which aims to protect 30% of terrestrial and marine ecosystems by 2030. However, such initiatives often face difficulties in securing long-term funding for conservation and for the value of ecosystem services to be recognized. Costa Rica, one of the co-chairs for the HAC for Nature and People, has used payments for ecosystem services as a tool for achieving conservation goals.

1.2. Payments for Ecosystem Services in Costa Rica

Payments for ecosystem services (PES) are a market-based policy instrument used to provide incentives to land owners for the provision of a variety of ecosystem services, including clean water, biodiversity protection, and carbon sequestration. PES are a relatively recent mechanism for economic valuation and for providing economic incentives for conservation, becoming a part of the global movements around conservation and development in the late 1990s and early 2000s, but they have grown to be applied in a variety of different ways (Gómez-Baggethun & Ruiz-Pérez, 2011). In 2018, there were over 550 programs globally with combined USD 36 billion in payments (Salzman et al., 2018).

While mechanisms for commodification of ecosystem services have been critiqued for placing market values on services that cannot be adequately valued or should not be on the market at all, PES have also been increasingly used by conservationists as a way to convey the value of the services ecosystems provide and to provide funds where traditional methods for funding conservation have failed (Gómez-Baggethun & Ruiz-Pérez, 2011).

Costa Rica, a small country in Central America that has been recognized for its achievements in environmental conservation, has one of the only national-level long-term PES programs in existence (FONAFIFO, 2022). The Costa Rican national PES program (*Programa de Pagos por Servicios Ambientales* or PSA program) was started in 1997 and is considered one of the programs that has made Costa Rica a conservation frontrunner. The program is managed by the National Forestry Financing Fund (FONAFIFO) and is funded at a national level by a sales tax on all fossil fuels, of which 3.5% is designated to the PSA program, but also from other public funds and international organizations like the World Bank (REDD+ Costa Rica, 2017).

The duration of the PSA program has allowed for it to grow and change over time, and the program has been a model for other PES programs in other parts of the world, making it an interesting case to investigate because of its longevity and legacy (Sánchez-Chaves & Navarrete-Chacón, 2017). Additionally, the PSA program has recently been recognized for its success with awards such as the Earthshot Prize in 2021 (Rico, 2021).

1.3. Institutional context for the PSA program

The Costa Rican PSA program is one policy in a well-established and robust national environmental governance system, especially regarding forestry. Costa Rica successfully reverted a stark trend in deforestation during the 20th century, going from around 20% forest cover in the early 1980s to around 57% forest cover now, depending on how forest cover is calculated (Green Climate Fund, 2020; Madriz, 2022). Several policies and initiatives are credited with facilitating the conservation and restoration of forest ecosystems in Costa Rica, including efforts to protect existing forest, to reforest and regenerate natural ecosystems, to promote sustainable use of forests, and to reduce deforestation and degradation of forest.

During much of the 20th century, forest cover in Costa Rica decreased, and while there were many people, organizations, and institutions already managing and protecting forests and other ecosystems, one of the first actions to protect the remaining forests was to create protected areas. Costa Rica's terrestrial protected areas now cover nearly 30% of the country and are one of the cornerstones of Costa Rica's conservation tradition. The National System of Conservation Areas (SINAC), the current entity that manages the protected areas of Costa Rica, was created in 1998 with the Biodiversity Law (Law no. 7788). Just before that, the Ministry of Environment and Energy (MINAE) was created in 1995 with the Organic Environmental Law (Law no. 7554). The Organic Environmental Law also includes the right of Costa Rican citizens to a healthy environment and the responsibility of the government to protect this right.

Also in the 1990s, Costa Rica created some of the foundations of the country's forest management strategy, including the Forestry Law (Law no. 7575). Enacted in 1996, the Forestry Law banned cutting of forest (defined as a minimum of 2 hectares, 70% forest cover, and 60 trees per hectare) and established several policy mechanisms for protecting and promoting sustainable use of the country's natural ecosystems. With this law, the National Forestry Office (ONF) was created to govern sustainable use of forest products and the Payments for Ecosystem Services (PSA) program was created to compensate land owners for ecosystem services. The country's PSA program and protected areas together cover 70% of the forested areas in the country.

Additional laws related to environmental management include laws on soil management, land use planning, agriculture and fisheries, and indigenous lands. Within the Ministry of Environment and Energy, a number of institutions to govern different areas of environmental management have also been created, some of which are also involved, directly or indirectly, in forest management and ecosystem services. Examples of such entities include water management institutions, data management networks, permitting and technical bodies, and a commission on biodiversity management.

In addition to its commitment to reversing deforestation, Costa Rica has made important commitments to protecting and increasing carbon reservoirs through managing land use change. Costa Rica has been steadily decreasing its emissions from the forest sector since the late 1980s (Costa Rica, 2021). In fact, the forest sector in the country is now a net carbon sink (Costa Rica, 2021). Costa Rica was one of the countries to propose the initiative for Reducing Emissions from Deforestation and Forest Degradation (REDD+) at the United Framework Convention on Climate Change (UNFCCC) COP 11 in 2005 and has been involved in the implementation of REDD+. Costa Rica has received funds for capacity building and reducing greenhouse gas (GHG) emissions through the Forest Carbon Partnership Facility (FCPF) and the Green Climate Fund (GCF), which provide additional funds for provision of ecosystem services by forests. With many similar goals, the PSA program and REDD+ in Costa Rica both target mitigation of GHG emissions through carbon sequestration and stocks.

1.4. Evaluating the PSA program

While PES have been increasingly used as mechanisms to fund conservation and protect or provide ecosystem services, measuring their effectiveness is challenging, because many of the ecosystem services that PES programs aim to provide compensation for are not simple to measure and quantify and programs may not have the resources to systematically monitor the provision of these services. Since PES programs are still a relatively new tool in conservation, measuring their success is still a developing field. In addition, many programs, including the PSA program, seek to achieve a variety of environmental and socioeconomic goals, which frequently results in tradeoffs between the different goals. Costa Rica's PSA program is not an exception. Despite its longevity and recognition, the PSA program does not have a comprehensive and clear mechanism for monitoring the provision of ecosystem services within the program.

Although evaluating the effectiveness of PES programs in providing ecosystem services can be a challenge, it is important to understand the strengths and weaknesses of this type of program and to continue to improve upon it, especially as the PSA program has been used as a model for other programs. Outside of the internal evaluation and monitoring of the PSA program by FONAFIFO, in Costa Rica, there have been several studies measuring different environmental services and evaluating different aspects of the environmental effectiveness, which are discussed further in Chapter 2. These studies have varied in their geographic scope and in the time periods they cover, as well as the ways in which they have measured ecosystem services. At the same time, the REDD+ Secretariat in Costa Rica has developed a consistent methodology for measuring changes in forest carbon stocks, emissions, and sequestration over time, providing data on one of the ecosystem services that the PSA program covers: carbon storage and sequestration. Using this data on carbon to evaluate this ecosystem service in the Costa Rican PSA program can provide new insight into the environmental impacts of the program and the changes within it over a more comprehensive temporal and spatial scale than found in previous literature.

1.5. Research aim

While acknowledging that the PSA program of Costa Rica has several policy goals, the primary objective of this study is to contribute to the understanding of the effectiveness of the PSA program design in delivering ecosystem services, especially carbon storage and sequestration.

To evaluate the effectiveness of the PSA program in providing this ecosystem service, I will use a time series of carbon stock data at the national level to explore the relationship between PSA program design and management strategies and carbon stocks through the following questions:

1. To what extent are the goals set by the program on carbon storage and sequestration for climate change achieved?
2. Do spatial targeting and prioritization criteria prioritize areas with greater carbon stocks or carbon density?
3. Are certain contract types associated with higher carbon stocks or carbon density?

Because the institutional framework has been important in determining the policy goals of the Costa Rican PSA program, a secondary goal in this research is to describe some of the institutional factors that may influence the environmental outcomes of the PSA program and make relevant recommendations.

1.6. Scope

While there are now many countries and regions globally with PES programs and many other mechanisms for conservation in Costa Rica that are related to provision of ecosystem services, this study focuses on Costa Rica and the *Pagos por Servicios Ambientales* (PSA) program, a payments for ecosystem services program that is managed by FONAFIFO under the Ministry of Environment and Energy. This study focuses on mitigation of GHG emissions through carbon storage and sequestration, which is one of the four ecosystem services included in the PSA program, which also has other policy goals such as providing income to small landowners. Carbon density data and spatial data on properties in the PSA program are available from 2012-2020, so data analyses focus on trends in carbon stocks during that period.

1.7. Ethical considerations

Data used in this study are either publicly available or were provided to me for use in this study and the authors of the data sets and tools used have been credited accordingly. Any identifying information in the data sets has been removed in the published study. GDPR regulations regarding data collection and storage have been followed to ensure the protection of any personal data in the data sets used.

While organizations and institutions involved in the Costa Rican PSA program have provided data and expertise in the field, they have not been involved in analysis of data and results and their role should not compromise the objectivity of the study. The views expressed in this study do not necessarily represent those of any institution that the author may be affiliated with.

1.8. Outline

Following this introduction, in Chapter 2, context is provided on the effectiveness of PES programs, the PSA program in Costa Rica, governance of the PSA program, and carbon accounting in Costa Rica. In Chapter 3, the methodologies for the data sets being used and data analysis are presented. In Chapter 4, results from analysis of data are presented and in Chapter 5, those results are discussed in the context of relevant research and significance. Lastly, in Chapter 6, recommendations are provided based on the results of the study.

2 Context

There are many possible ways to evaluate a PES program like the Costa Rican PSA program. This chapter provides information on the context for evaluating a policy like this one, from key concepts and methods to relevant parameters for evaluation of the effectiveness of the PSA program. Section 2.1 briefly discusses the complexities involved in how to evaluate environmental policies and specifically important concepts related to evaluating PES programs as a policy. Section 2.2 provides an overview of the methodologies that have been used in evaluating the environmental effectiveness of the PSA program and some relevant considerations for improving evaluations. Section 2.3. highlights the legal framework of the PSA program and key program design features, and Section 2.4. provides an overview of the available data on carbon stocks in Costa Rica, as the ecosystem service chosen for evaluating ecosystem service provision in this study.

2.1. Evaluation of PES programs

Payments for ecosystem services programs are an example of economic policies, where the primary intended effect is a change in environmental service provision. Mickwitz (2003) highlights some of the challenges in evaluating environmental policies, such as complexity in the problems to address, long temporal scopes, uncertainty in relevant data, and many stakeholders. These challenges continue to be relevant for many PES programs today. PES programs are a relatively recent mechanism for conservation, but have been increasingly well-studied. Between 2010 and 2015, on average 1,715 studies were published per year on the topic of PES (Börner et al., 2017). Many of these studies evaluate aspects of the effectiveness of PES programs and many are challenged by availability and uncertainties in relevant data and the complexity of understanding the effects on the socio-ecological systems these programs are embedded in.

While measuring achievement of the results directly intended by the goals of the policy, continues to be a relevant evaluation, Mickwitz (2006) also emphasizes that considering multiple criteria upon which to evaluate a policy can facilitate a more comprehensive evaluation. Many of the criteria described by Mickwitz (2006), are utilized in environmental evaluations of PES programs.

One of the main ways that effectiveness of PES programs has been measured is as the provision of ecosystem services with the program, compared to a scenario without the program. Additionality refers to the impact attributable to the program on ecosystem service provision (Börner et al., 2017). There are a number of factors that can affect the additionality of a PES program. One of these is adverse selection bias, where land owners that would have complied with program terms regardless of the payments participate in the program, reducing its additionality (Börner et al., 2017). Compliance by participants is also an important factor affecting additionality, where lowered compliance reduces positive effects on ecosystem services (Börner et al., 2017).

However, not all PES programs have the explicit goal of additionality, and many have multiple policy goals, including socioeconomic goals like poverty alleviation. This may impact the additionality of a PES program when tradeoffs between policy goals occur. An institutionalist framework for evaluating PES programs advocates for measuring effectiveness with the program's stated goals and for incorporating the impact of the PES program and associated policy mix in its entirety (Legrand et al., 2013). Assessing the effectiveness in achieving socioeconomic goals or the effects on socio-ecological systems is another component of measuring effectiveness, especially in programs with multiple policy goals.

A secondary factor that is often considered in evaluating PES effectiveness are spillover effects. Spillover effects are impacts that are outside the PES program scope. Spillover effects can decrease or increase provision of ecosystem services and can be observed within PES participants or non-participants (Börner et al., 2017). Spillover effects can vary in their impact relative to the PES program itself and can be difficult to quantify (Wunder, 2007). A related concept is motivation crowding, or how a PES program could affect the intrinsic motivation of participants and non-participants toward conservation; if participants become more motivated by extrinsic benefits like PES, this could have a negative impact on conservation outside the scope of PES.

Permanence, the continuation of the effects of a program beyond its end or the end of contracts, is another factor affecting the effectiveness of PES programs. Few studies have addressed permanence, since PES programs are still relatively recent and data availability is a challenge, but this can be another measure of effects outside the scope of the PES program.

While many of the factors that can impact the effectiveness of PES programs and, in many cases, configurations that have led to more favorable outcomes have been identified, more research and empirical data can provide clarity regarding ways to improve PES programs, as they continue to be one of the more effective mechanisms for conservation (Börner et al., 2017).

2.2. Environmental effectiveness of the PSA program

There are several main ways that the Costa Rican PSA program has been evaluated, including its economic efficiency, its social effects and their distribution, its governance and structure, and its environmental effectiveness. Because the program has existed for over 25 years, there is a range of aspects being evaluated, but also time periods and regions being evaluated and methods for assessing the program.

The Costa Rican PSA program is one of the most studied PES programs, and a number of studies have evaluated the environmental effectiveness of the program. These studies measure different environmental variables, primarily aiming to measure one or more of the ecosystem services that the program pays to safeguard. In many cases, this is done through a proxy for ecosystem services such as forest cover, as measuring the services themselves can be challenging and resource intensive. Some of the key methods for measuring environmental variables to evaluate the PSA program have been geospatial or remote sensing, interviews or other types of consultation with key stakeholders, and sampling.

With geospatial data, one mechanism to evaluate the effectiveness of the PSA program is observing differences in forest cover or land use type over time or between different properties, for example comparing properties with PSA contracts to properties not within the program. Another mechanism using geospatial data is to approximate avoided deforestation by estimating the deforestation rate of non-PSA land and comparing this to the deforestation rate on properties that participate in the PSA program (Pagiola, 2008; Pfaff et al., 2008). Some studies have also used remote sensing data to model carbon storage, gross deforestation, soil erosion control, and habitat suitability (Pagiola, 2008; Havinga et al., 2020). In empirical methods, one study took several measurements of biodiversity and carbon sequestration through soil sampling at PSA properties and then monitored the changes in these ecosystem services, in addition to taking geospatial measurements (Rasch et al., 2021). Other studies also monitor biodiversity and different types of ecosystem services on-site over time to detect changes that could be attributed to the PSA program (Calvet-Mir et al., 2015). In qualitative methods, several studies have used surveys and interviews to gather the perceptions of project participants, managers, or other key stakeholders on the performance of the program or changes in ecosystem service provision or behavior (Cole, 2010; Calvet-Mir et al., 2015; Arriagada et al., 2012).

In general, the program has been regarded to have low additionality, meaning a small effect in comparison to a scenario in which the PES program were nonexistent, although this varies depending on the methodology and scope of the evaluation (Legrand et al., 2013). However, it has also been considered a program that had been effective in its stated goals, which do not include additionality (Legrand et al., 2013). Many of the studies on the Costa Rican PSA program have found results indicating some effectiveness of the program in delivering environmental benefits. Havinga et al. (2020) found that properties with PSA contracts for at least a two-year period stored an additional 9 ton C ha-1 compared to other forested land, noting that these findings suggest that longer-term participation in the PSA program may result in environmental benefits. A study by Arriagada et al. (2012) focused on the Sarapiquí region of Costa Rica also found that forest cover on properties with PSA contracts increased in comparison with properties not in the PSA program. A study by Cole (2010) on participants in the agroforestry contract type of the PSA program found that land owners with PSA properties planted more trees and more tree species than other land owners. In a study focused on the effects of both the PSA program and the 1996 ban on forest conversion in the San Juan-La Selva Biological Corridor, Morse et al. (2009) found a decrease in the rate of natural forest loss from -1.43% to -0.10%/year and that areas targeted by the PSA program retained forest while areas not targeted by the PSA lost forest cover. Rasch et al. (2021) used empirical data taken before and after the Regional Integrated Silvo-pastoral Ecosystem Management Project, a PES program carried out by the CATIE (Tropical Agricultural Research and Higher Education Center) to demonstrate permanence of improved carbon and biodiversity ecosystem services nine years after the end of the program.

While many of the studies on the environmental effects of the PSA program found some improvement in ecosystem services related to the PSA program, other researchers found mixed results or no changes attributable to the PSA program. A study by Pfaff et al. (2008) showed little or no change in the rate of deforestation on properties with PSA contracts and noted that better targeting of areas with greater deforestation risk could improve the environmental effectiveness of the program. Pagiola (2008), in a review of studies from the first decade of the PSA program, found that PSA properties generally had higher forest cover than non-PSA properties, but also that it was difficult to systematically attribute these changes to the PSA program. Similarly, a review of PES programs done by Calvet-Mir et al. (2015) found that in previous studies, the effectiveness of the PSA program depended on the methodology and geographic scope. A review by Daniels et al. (2010) found no lowered deforestation at the national level, but some regional evidence of avoided deforestation and Legrand et al. (2013) found a similar result of low additionality at the national level, but some evidence at a regional level, increasing through time.

While results from previous assessments of the environmental impacts of the PSA program have been mixed, many of these studies have been limited in terms of spatial or temporal scope and many have relied on proxies for ecosystem services. Previous studies of the PSA program highlight the need for more empirical data, as well as counterfactuals in future studies, since many have noted the difficulties in attributing environmental changes to the PSA program and in accounting for external factors related to environmental changes.

2.3. PSA program governance

Costa Rica's National Forestry Financing Fund (FONAFIFO) and the PSA program were established in 1996 by the Forestry Law, with the goal to "finance, for the benefit of small and medium-sized producers, by means of credit or other mechanisms to promote forest management, whether managed or not, the processes of afforestation, reforestation, forest nurseries, agroforestry systems, recovery of degraded areas, and technological changes in the use and industrialization of forest resources. It will also capture funds for the payment of environmental services provided by forests, forest plantations, and other activities necessary to strengthen the development of the natural resources sector, which will be established in the regulations of this law (Asamblea Legislativa, 1996)."[1] This continues to be the legal framework for the PSA program, although the mechanisms for achieving these goals are managed internally by FONAFIFO. Strategic goals for management of the PSA program can be found in the organization's strategic plans, including strategic goals on governance, socioeconomic aspects, and environmental aspects of the program (Fondo Nacional de Financiamiento Forestal, 2015, 2019).

As stated in the legal framework, the PSA program was designed to finance sustainable forest management practices by compensating land owners for the ecosystem services that their properties provide. The ecosystem services that the PSA provides compensation for are greenhouse gas emissions mitigation through carbon sequestration and storage, biodiversity conservation, hydrological services, and scenic beauty. The PSA program has several contract types for providing these payments, including forest protection, reforestation, natural regeneration, and agroforestry. Forest protection has been the contract type that the majority of contracts have been under (Sánchez-Chaves & Navarrete-Chacón, 2017). Many of the other contract types were added at various stages of the program or have been prioritized or deprioritized at different stages, in efforts to better manage the program according to relevant conditions and goals (Sánchez-Chaves & Navarrete-Chacón, 2017).

An important factor in the way that FONAFIFO manages the PSA program is that it aims to renew contracts with land owners, making it a more stable source of income for land owners. In fact, previous participation in the program is one of the prioritization criteria for contract allocation. The PSA program has consistently received more applications than funds it has for PES, so selection criteria are used to prioritize applicant properties in line with the goals of the program and ecosystem services covered, including being located in protected areas, indigenous territories, key watersheds, being of high conservation value, and belonging to smallholder farmers (Sánchez-Chaves & Navarrete-Chacón, 2017). These management choices contribute to targeting the provision of ecosystem services and other goals of the program, which is one of the ways in which effectiveness of PES programs have been evaluated.

2.4. Carbon stocks and sequestration of Costa Rican forests

In selecting the base to use for measuring the effectiveness of the PSA program, I assessed the availability of data on the different ecosystem services covered by the program, which varies for each ecosystem service in terms of comprehensiveness and scale. Of the ecosystem services covered in the PSA program, one ecosystem service that researchers have gathered empirical data on for decades is carbon, through measurements of carbon stocks, sequestration, and emissions of different ecosystems and land use types. However, national commitments to international agreements such as the Paris Agreement and contracts for emissions reductions or carbon credits provided the momentum to quantify carbon stocks, sequestration, and emissions systematically at the national level.

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[1] Translation by author. The original text and amendments of the Forestry Law can be found at: http://www.pgrweb.go.cr/scij/Busqueda/Normativa/Normas/nrm_texto_completo.aspx?nValor1=1&nValor2=41661.

The first systematic quantification of carbon stocks in forest at the national level was in the National Forest Inventory (IFN), with data taken in 2013 and 2014 on 280 plots each of 1 hectare, covering all major forest types in the country (Emanuelli et al., 2016). At each plot, key plant traits, diversity, biomass, and carbon content were measured in different sections of the plot, including measurements of soil, leaf litter, understory plants, saplings, and canopy trees (Emanuelli et al., 2016). Prior to site visits, Landsat satellite imagery was used to classify land use types of Costa Rica, identify forest types, and select sampling plots such that each type of forest would be represented proportionally in sampling (Emanuelli et al., 2016). The carbon stock data from the IFN was extrapolated to the entire country, with an estimate of 2,950,174,696 tons CO_2, with a 6.1% margin of error.

A second effort to systematically quantify carbon stocks in Costa Rica was done by the REDD+ Secretariat in Costa Rica. This effort goes beyond quantification of carbon stocks to measure emissions and sequestration, as well as degradation and enhancement of forests. To be able to measure carbon in a systematic way that shows changes, methodologies were created by AGRESTA (2015) using Landsat and Random Forest to generate land cover maps that are comparable between each other. This was done starting with the year 1986 to present. Carbon data was extrapolated to the national level using carbon data from the National Forest Inventory and from literature and a tool created by Carbon Decisions International with the forest reference levels. Using these tools, for the last reported period (2018-2019), the REDD+ Secretariat reported 3,283,023 t CO_2e in emissions reductions for the country. The time series of carbon maps has also allowed the REDD+ Secretariat to demonstrate that the emissions from land use change have been decreasing and that the country's forests are now a net carbon sink.

At the same time, Costa Rica has produced greenhouse gas inventories in line with the Paris Agreement. The REDD+ maps and carbon densities data use the same land cover categories to maintain compatibility and share many of the methodologies laid out by the Intergovernmental Panel on Climate Change (IPCC). In 2017, the last GHG inventory, the Forestry and Other Land Uses (FOLU) sector was reported to have been a net carbon sink for -2968,35 Gg CO_2-e (Costa Rica, 2021). The FOLU sector is the only sector covered in the GHG inventory that is a net sink (Costa Rica, 2021).

A recent report to present trends in carbon in Costa Rican forests was included in the State of the Nation Report for 2021, a publication created by a program under the Office of the Ombudsperson and the four public universities of Costa Rica (Durán Monge & Aragón Ramírez, 2021). In this report, Durán Monge & Aragón Ramírez (2021) found that the forests of Costa Rica have contained an average stock of 1.055 $GtCO_2$-e between 1986 and 2019. The trend in carbon stocks shown in this report was a decrease after 1986, followed by a period of little change and a recent increase in carbon stocks (Durán Monge & Aragón Ramírez, 2021). As of 2019, carbon stocks have not recovered to 1980s levels and changes in carbon stocks in forests have been unequally distributed in the country, with protected areas harboring a disproportionately large amount of the carbon stocks in the country (Durán Monge & Aragón Ramírez, 2021).

These reports, many of them created to fulfill different commitments to international institutions, now provide a baseline with comparable methodologies to continue monitoring carbon stocks, emissions, and sequestration at a national level. While they each have important assumptions that influence the resulting data and analyses, researchers have highlighted the importance of using these reports to improve governance of forests for the sector to continue to be a carbon sink (Durán Monge & Aragón Ramírez, 2021).

3 Research Design and Methods

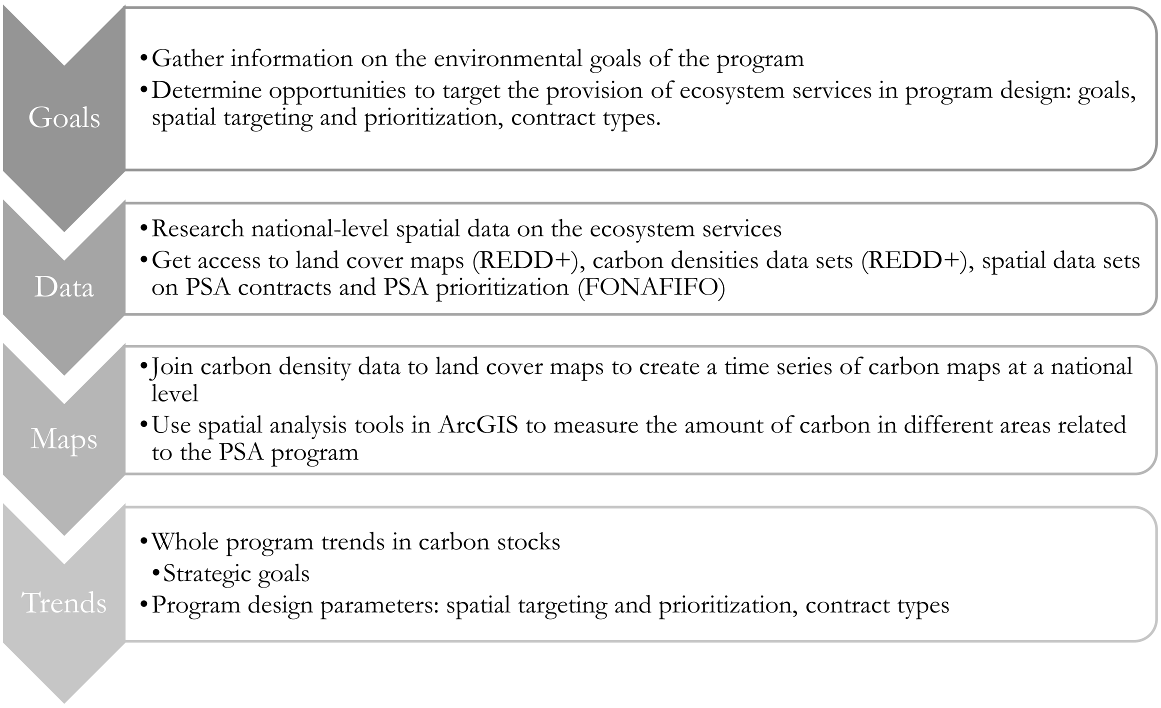
Section 3.1. describes the research design for this study, drawing from the background concepts in Chapter 2. Section 3.2. describes the different data sets that were used for this study and the methodology for creating a time series of carbon maps and for calculating carbon stocks within the PSA program.

3.1. Research design

In evaluating the effectiveness of an environmental policy like the PSA program, Mickwitz (2003) outlines a basic expectation of having some type of input, expected output, and outcomes. For the PSA program, in a general sense, one of the fundamental inputs is the financial incentive and the expected outputs are ecosystem services, while the outcomes could be effects related to the program. However, while most types of land use in Costa Rica would provide some amount of ecosystem services, different elements of program design can directly or indirectly impact the quantity and type of ecosystem services provided on properties in the PSA program. To try to understand the effectiveness of the program in providing ecosystem services, I identified program design and management strategies that could target the outputs in terms of ecosystem services: goal setting or institutional planning, targeting or prioritization, and categorization in contract types.

I chose to evaluate the program using the ecosystem services themselves, since they are the main expected output of the program. Data availability and scope influenced my choice of the ecosystem service to use to evaluate the PSA program. The PSA program provides compensation for the provision of four ecosystem services: GHG mitigation through carbon sequestration and storage, biodiversity conservation, hydrological services, and scenic beauty. However, carbon storage and sequestration was the ecosystem service with the most comprehensive data set in terms of temporal and spatial scale.

To evaluate the environmental effectiveness of the Costa Rican PSA program, I considered effectiveness to be broadly the outcomes observed in comparison with the stated or understood goals of the program. Because not all the program design elements had a specific goal to compare to, I chose to compare either to a goal, a baseline, or between the variations within the management choice. The steps involved in the methods in the study are summarized in Figure 1.



Goals
- Gather information on the environmental goals of the program
- Determine opportunities to target the provision of ecosystem services in program design: goals, spatial targeting and prioritization, contract types.

Data
- Research national-level spatial data on the ecosystem services
- Get access to land cover maps (REDD+), carbon densities data sets (REDD+), spatial data sets on PSA contracts and PSA prioritization (FONAFIFO)

Maps
- Join carbon density data to land cover maps to create a time series of carbon maps at a national level
- Use spatial analysis tools in ArcGIS to measure the amount of carbon in different areas related to the PSA program

Trends
- Whole program trends in carbon stocks
  - Strategic goals
- Program design parameters: spatial targeting and prioritization, contract types

Figure 1. Steps in the methodology of this study.

3.2. Methods

To be able to evaluate the environmental effectiveness of the PSA program, I researched the national-level spatial data available on ecosystem services that are compensated by the PSA program. I chose to use data sets and maps from REDD+ that provide carbon densities and land cover at the national level and a data set from FONAFIFO with PSA contracts at a national scale. These data sets provided the base with which I created a time series of carbon maps for Costa Rica 2011-2020 and used these maps to calculate the carbon in different areas of the PSA program over time.

Section 3.2.1 describes the data sets created by REDD+ and FONAFIFO that I used as a base for my study, including relevant details from the methodologies by which the data sets were created. In section 3.2.2, some details around sources of uncertainty in the base data sets from REDD+ are included. Section 3.2.3 describes the methodology I used to create a time series of carbon maps, including assumptions made in this study in using the data sets described in the previous sections. Section 3.2.4 describes the methodology used in this study for calculating carbon stocks in the PSA program and section 3.2.5 outlines some basic concepts in analyzing the carbon stock data.

3.2.1. Sources of data

To evaluate the effectiveness of the PSA program in Costa Rica, I used three sources of data created by FONAFIFO and the REDD+ Secretariat in Costa Rica. This section describes each of these three sources of data. Additionally, while the full methodologies with which these data sets were created by REDD+ and FONAFIFO are described in reports created by these institutions, in this section I also include some details from these methodologies that are relevant to the way in which I used the data sets in this study.

The scale of these sources and, therefore, my data analyses as well, is the country of Costa Rica, excluding Isla del Coco, which is a protected area that does not qualify for the PSA program.

3.2.1.1. REDD+ historical series of land cover maps

In order to generate activity data on carbon emissions and sequestration and generate the reference level for Costa Rica, the REDD+ Secretariat has created a historical series of land cover maps using a consistent methodology that allow for comparisons through time (AGRESTA, 2015).[2]

These maps were created for several year intervals starting in 1986 and were created at two-year intervals since 2011. These maps were created using satellite imagery from Landsat 4 TM, 5 TM, 7 ETM+ and 8 OLI/TIRS[3] taken during the same season and over the course of several months (not more than 14 months) to reduce the effect of cloud cover. The maps were radiometrically normalized following the IR-MAD (Iteratively Reweighted Multivariate Alteration Detection) described by Canty and Nielsen (2008).

Classification of land cover for these maps was done using the Random Forest machine learning method. Land cover was classified into the following land cover categories that were used in this study: forests, croplands (annual and permanent), grasslands, paramo, urban areas, and bare soil. Forests were further categorized into five forest types: wet and rain forests, moist forests, dry forests, mangrove forests, and palm forests and then within each forest type, forests were classified as primary or new forests (Table 1, Figure 2). Primary forests are forests that have been classified as forest since before the first map (1986) and new forests are forests that have appeared in areas that were previously categorized into a different land cover type. Based on consultation with experts during the creation of the land cover maps, all forest types are assumed to appear in the maps at about 4 years of age, with the exception of dry forests, which are presumed to appear at 8 years of age.

Table 1. Land cover types in the REDD+ historical series of land cover maps. Source: REDD+.

Forests	Wet and rain forests	Primary forest New forest (age cohorts)
	Moist forests	
	Dry forests	
	Mangroves	
	Palm forests	
Grasslands		
Urban areas		
Croplands	Annual	
	Permanent	
Other land cover	Bare soil	
	Paramo	

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[2] The elements of the methodologies for the creation of the REDD+ historical series of land cover maps that are most relevant for this study are explained in section 3.2.1.1; complete methodologies for production of the maps can be found in reports by AGRESTA (2015), Ministry of Environment and Energy of Costa Rica (2021), Córdoba Peraza (2020), Córdoba Peraza (2020), and Ministry of Environment and Energy of Costa Rica (2019).

[3] Landsat satellites vary in the time of deployment, resolution and qualities of data collected.

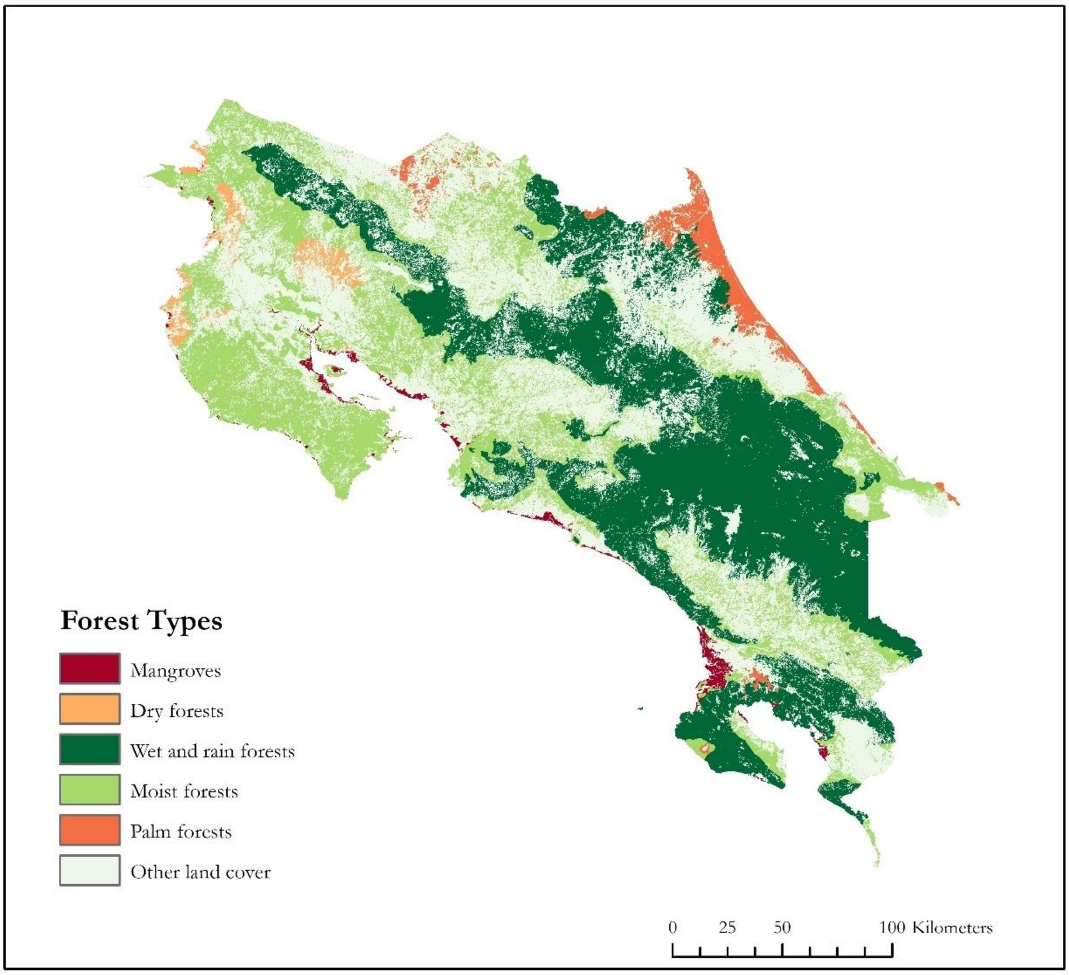

Figure 2. Map of forest types in the 2019 REDD+ land cover map. Data source: REDD+.[4]

After classification, some manual edits to the land cover classification were made, including visual identification of urban and bare soil classes using RapidEye high resolution images. Additionally, forest plantations were categorized as forest and the five forest types were classified based on maps of Holdridge (1966) life zones and masks created with potential areas for mangrove forests, palm forests, and paramo.

The resulting maps have a resolution of 30 m x 30 m and a minimum mapping area of 11 pixels or 0.99 ha, in accordance with the definition of forest used for REDD+, which is a minimum of 1 hectare and 30% canopy cover (see examples in Figure 3).

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[4] Created by author using data from REDD+.

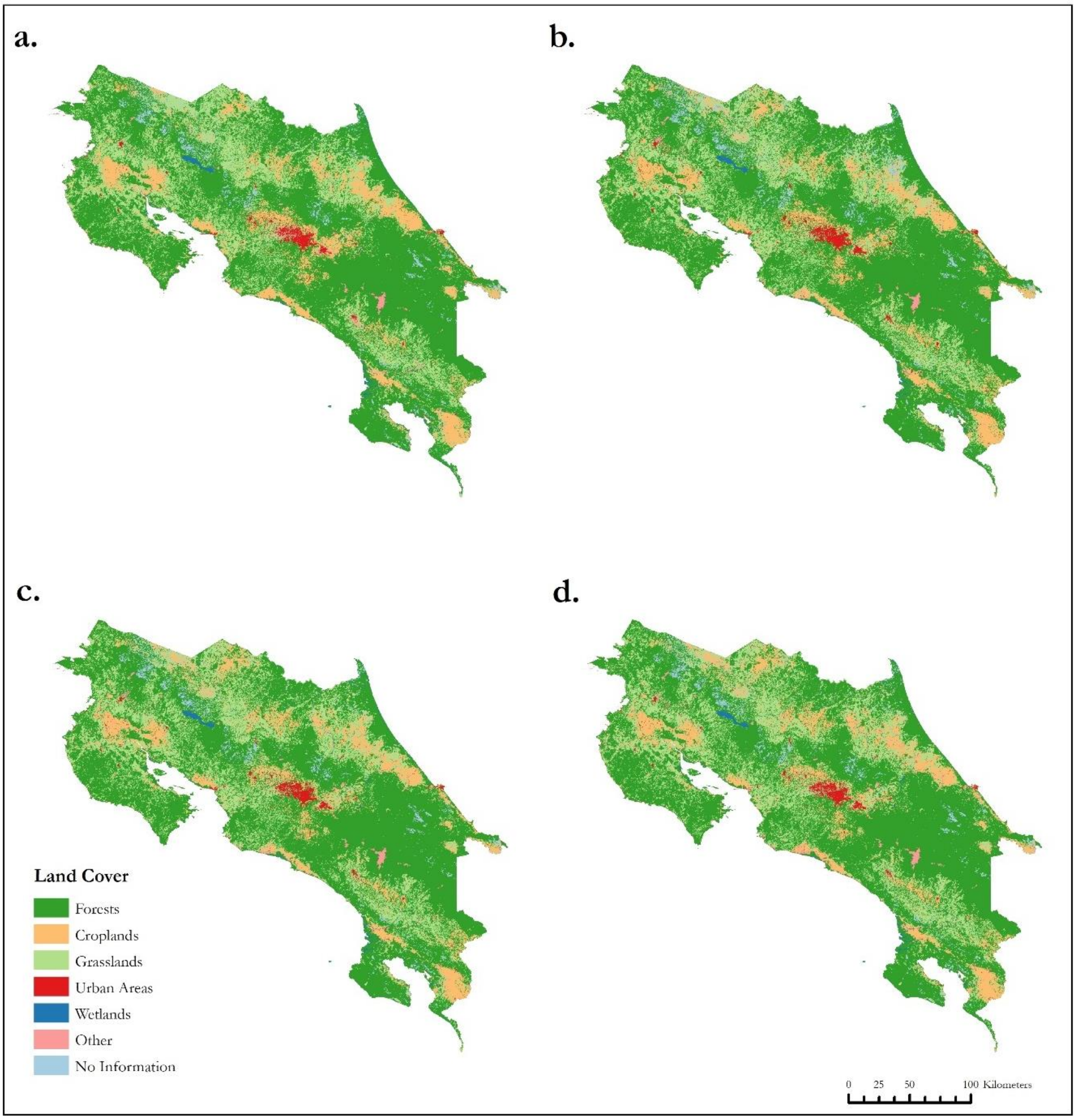

Figure 3. REDD+ historical series of land cover maps: ***a.*** *2013,* ***b.*** *2015,* ***c.*** *2017,* ***d.*** *2019. Data source: REDD+.*[5]

3.2.1.2. Forest Reference Level (FREL) tool

The Forest Reference Level (FREL) tool created by consulting firm Carbon Decisions International for the REDD+ Secretariat in Costa Rica is used to calculate the carbon stocks and carbon activity data for each year (Pedroni & Villegas, 2016).[6]

Data on carbon densities can be found in a separate database created for developing the FREL tool and determining the carbon reference level. The database was also created by Carbon

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[5] Created by author using data from REDD+.

[6] The most relevant elements of the methodologies for the creation of the FREL tool for this study are explained in section 3.2.1.2; complete methodologies for the FREL tool and carbon densities data set with additional details can be found in reports by Pedroni & Villegas (2016), Ministry of Environment and Energy of Costa Rica (2019), and Ministry of Environment and Energy of Costa Rica (2021).

Decisions International using available empirical data on carbon densities in different types of forests and land use. The carbon densities database includes some sites from the 2013-2014 National Forest Inventory and sites from other sources, for a total of nearly 500 sites with carbon density data (Pedroni & Villegas, 2016). Data that was not from the National Forest Inventory was compiled through a metanalysis that targeted literature measuring carbon, biomass, or biometric data on carbon reservoirs.

Carbon density data in the dataset are classified by the same land use types used in the REDD+ historical series maps and also categorized by biomass reservoir. While the carbon density data were originally classified into 17 biomass reservoirs, because of the distribution of the data, some categories were aggregated, leaving 4 categories that were used (Table 2). Because of the availability and distribution of data, carbon in all belowground biomass was calculated using the ratio by Cairns et al. (1997) and carbon in secondary forests was calculated using modified versions of models by Cifuentes-Jara (2008), applying maximum carbon values for primary forest in the carbon densities data set as the maximum values. In mangroves and palm forests, where biomass accumulation models were not available, linear models were used. Dead wood and litter in secondary forests were assumed to be present in the same ratio to aboveground biomass as in primary forests, which may underestimate these values because forests in early successional stages may have remaining dead biomass from the previous land cover (Pedroni & Villegas, 2016). Due to differences in the methods for collecting soil organic carbon (SOC) measurements, this carbon reservoir was excluded from the data set.

Table 2. Carbon reservoirs used to calculate total carbon densities by land cover type. Source: Pedroni & Villegas (2016).

Reservoir	**Abbreviation**	**Data**
Above ground biomass	AGB	Non-woody biomass was not included in every forest sample, but is considered a small fraction of the total aboveground biomass in forests.
Belowground biomass	BGB	Calculated as a ratio from AGB
Dead wood	DW	In secondary forest, calculated as the same ratio to AGB as in primary forest
Litter	L	In secondary forest, calculated as the same ratio to AGB as in primary forest

Total biomass was calculated as the sum of each of the carbon reservoirs:

$$B_{tot} = B_{AGB} + B_{BGB} + B_{DW} + B_{L}$$

Conversion between biomass, carbon, and CO_2e was done using established ratios.

Carbon densities used in the FREL tool and in this analysis are arithmetic means of the data available for each carbon reservoir and land cover type, with the exception of above ground woody biomass for wet and rain forests, moist forests, and dry forests, where weighted means based on the sampled area were used (Table 3).

Table 3. Carbon densities by land cover, age, and carbon reservoir. Source: REDD+ and Carbon Decisions International.

Land cover		**Age**	**AGB**	**BGB**	**DW**	**L**	**Total**

Wet and rain forests	Primary forest		313.69	71.97	49.50	10.05	445.21
	New forests	4	34.50	9.33	3.74	0.36	47.92
		37	239.36	56.03	25.98	2.74	323.83
Moist forests	Primary forest		203.99	48.32	48.27	8.01	308.59
	New forests	4	44.14	11.72	5.10	0.85	61.81
		37	245.97	57.46	28.42	4.75	336.60
Dry forests	Primary forest		199.19	47.27	56.47	22.73	325.66
	New forests	8	15.64	4.49	1.88	1.51	23.51
		41	214.53	50.63	25.73	20.72	311.60
Mangroves	Primary forest		253.74	59.14	6.95	0.97	320.80
	New forests	4	10.15	3.01	0.26	0.03	13.44
		37	93.88	23.56	2.40	0.25	120.10
Palm forests	Primary forest		229.81	53.96	5.97	0.96	290.69
	New forests	4	9.19	2.74	0.29	0.05	12.27
		37	85.03	21.50	2.68	0.43	109.63
Croplands	Annual		83.57	21.16	-	-	104.72
	Permanent	4	55.90	15.27	0.81	5.06	77.04
		37	83.84	22.23	1.22	7.59	114.89
Grasslands			42.71	11.92	8.28	-	62.92
Urban areas			-	-	-	-	-
Other land cover	Bare soil		-	-	-	-	-
	Paramo		-	-	-	-	158.00

3.2.1.3. PSA contracts

The areas of PSA contracts used were from a dataset provided by FONAFIFO with contract numbers, the perimeter of the properties that were under contract, and the effective area of the property under contract for each year 2012-2022 (Figure 4). The dataset included properties under each of the different PSA contract types: forest protection, forest management, reforestation, natural regeneration, agroforestry systems, and mixed systems. Additionally, spatial data on criteria for determining priority for contracts in 2022 was also acquired from FONAFIFO, including conservation value, watersheds, indigenous lands, protected areas, and biological corridors. Although one of the prioritization layer related to social goals of the PSA program was included, it was not used in the analysis because it does not target an environmental goal of the program.

Because carbon densities are different between land cover types, the proportion of different PSA contract types in each year is expected to influence the total carbon stocks in the PSA program year to year. I compare the carbon densities of different contract types to illustrate this difference (Figure 13).

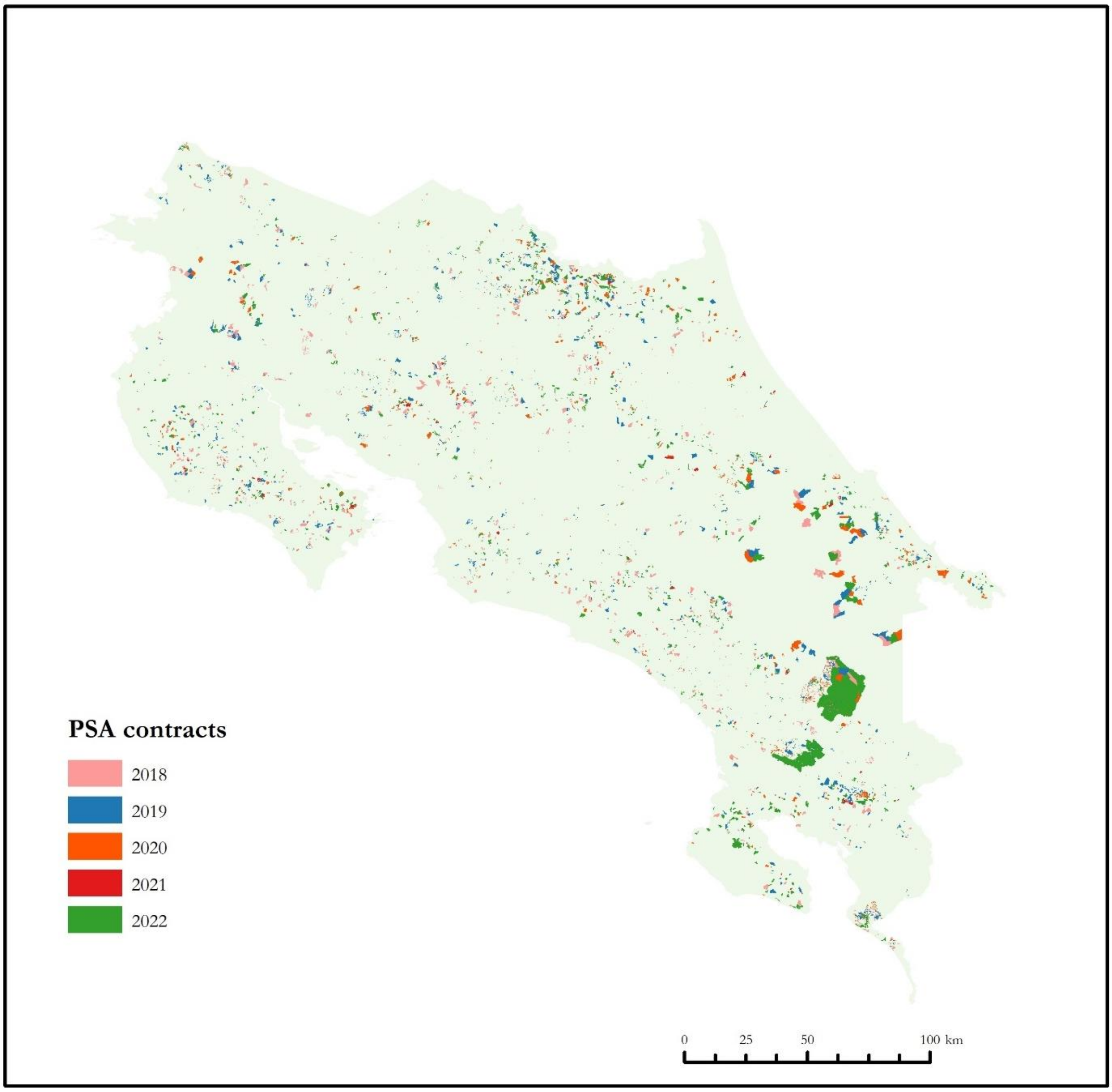

Figure 4. PSA contracts 2018-2022. Data source: FONAFIFO.[7]

3.2.2. Uncertainty

In analyses involving several types of data from a variety of sources over a large spatial and temporal scope, such as GHG inventories, there are many potential sources of error and bias. The IPCC guidelines on this topic emphasize identification of sources of uncertainty with the goal of improvement upon data collection and analysis (Eggleston et al., 2006). In the case of the REDD+ maps, several steps in the methodology by AGRESTA (2015) are aimed at reducing uncertainty and error, including manual verifications using high-resolution images, radiometric normalization, and validation of root mean square error (RMSE) of the control points[8]. For the carbon densities and FREL data from REDD+, the IPCC method for

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[7] Created by author using data from FONAFIFO.

[8] The elements of the methodologies for the creation of the REDD+ historical series of land cover maps that are most relevant for this study are explained in section 3.2.1.1; complete methodologies for production of the maps can be found in reports

propagation of error was used (Eggleston et al., 2006). The uncertainty of the carbon density data at the 90% confidence interval is summarized in Table 4.

Table 4. Uncertainty of carbon densities by land cover, age, and carbon reservoir at the 90% confidence interval. Data source: REDD+ and Carbon Decisions International.

Land cover		Age	AGB	BGB	DW	L	Total
Wet and rain forests	Primary forest		63.54	14.58	8.75	0.94	65.78
	New forests	4	2.91	0.79	0.32	0.08	3.03
		37	19.72	4.62	2.14	0.59	20.37
Moist forests	Primary forest		41.86	9.92	23.25	1.04	48.91
	New forests	4	3.35	0.89	2.43	0.13	4.23
		37	19.44	4.54	13.54	0.74	24.13
Dry forests	Primary forest		0	0	21.92	0.61	21.93
	New forests	8	1.25	0.36	0.54	0.13	1.41
		41	17.08	4.03	7.36	1.76	19.11
Mangroves	Primary forest		31.83	7.42	2.05	0.24	32.75
	New forests	4	1.27	0.38	0.10	0.03	1.33
		37	11.78	2.96	0.90	0.26	12.18
Palm forests	Primary forest		25.03	5.88	7.02	1.13	26.68
	New forests	4	1.00	0.30	0.36	0.05	1.11
		37	9.26	2.34	3.35	0.51	10.14
Croplands	Annual		9.69	2.45	-	-	9.99
	Permanent	4	39.02	10.66	0.29	2.41	30.82
		37	58.53	15.51	0.43	3.61	46.14
Grasslands			-	-	6.29	-	6.29
Urban areas			-	-	-	-	-
Other land cover	Bare soil		-	-	-	-	-
	Paramo		2.16	0.53	-	-	2.23

3.2.3. Carbon maps 2011-2020

I created carbon maps for Costa Rica using the FREL tool (described in section 3.2.1.2) and REDD+ time series maps (described in section 3.2.1.1) in ArcMap 10.8.1 using a model created to add carbon densities of each land cover type to each pixel in each of the 2011-2019 land cover maps. Several assumptions were made to assign carbon densities to each classification in the land cover maps, including a conversion of hectares (ha) to pixels of 1:11.11. Since the FREL tool includes carbon densities by years of growth for secondary forest and the REDD+ historical map series classifies new forests by cohort in which they change from other land cover categories to forest, I followed the assumption made with expert consultation for the REDD+ tools that forests of all types are 4 years of age when they appear in maps, except for dry forests, which appear at 8 years. Because I assigned each cohort and category of new forests in each land cover map as one age and carbon density at the younger end of the cohort, carbon values of new forests are conservative for most cohorts. This is especially true of forests that were new forests in the first map (1986), as I designated them all as being in the youngest age class (4 or 8 years) at that time, while likely many of these secondary forests were older and storing more carbon. Additionally, while the FREL tool carbon stocks data is disaggregated by carbon

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by AGRESTA (2015), Ministry of Environment and Energy of Costa Rica (2021), Córdoba Peraza (2020), Córdoba Peraza (2020), and Ministry of Environment and Energy of Costa Rica (2019).

reservoir and includes additional ways to measure carbon emissions and removals, such as from degradation, in this study I only used total carbon stock data.

Since the REDD+ land cover maps were created using satellite imagery over periods of up to 14 months, I used each carbon map I created based on the land cover maps to measure the carbon in 2 years of PSA contracts (Table 5). This is visualized in Figures 5-8.

Table 5. Land cover map and PSA contract cohorts.

REDD+ Land Cover Map	**PSA contracts**
2011	2012
2013	2013, 2014
2015	2015, 2016
2017	2017, 2018
2019	2019, 2020

3.2.4. Carbon calculation

Using the carbon maps, I used Zonal Statistics and other geoprocessing tools in ArcMap 10.8.1 to measure the carbon stocks within different areas relevant to the PSA program, including the areas under PSA contracts. Within the generated dataset on carbon stocks in the PSA program, I removed contracts with missing data. To use the data on PSA contracts, one assumption I made was that the duration of contracts followed a standard number of years per PSA contract type (Table 6). Because there is variation in the number of years per contract for certain contract types and some contract types have a range of contract lengths, this assumption could result in some contracts being assumed active for longer or shorter periods than the contract was for. Additionally, the available spatial data on prioritization of PSA contracts was for the 2022 contracts; however, based on consultation with FONAFIFO this layer was assumed to be similar to the prioritization in previous years for PSA contracts, as the criteria have not changed, only the weight of each criterion.

For the baselines used for comparison, the baseline used for the prioritization criteria was the area of Costa Rica not included in any of the priority areas. For contract types, two baselines were used with the goal of comparing properties in the PSA program to other properties with similar land cover that could have been in the program but were not. A mixed landscape baseline was used to compare contract types intended to increase forest cover (reforestation, agroforestry, natural regeneration, mixed systems, and forest management) which was composed of all land in priority areas excluding all contracts granted in 2012-2020. A forest baseline was used to compare with contract types intended to maintain existing forest cover (forest protection) which was composed of all forest within priority areas in 2011 excluding all contracts granted in 2012-2020.

Table 6. Contract length by type of contract. Data source: FONAFIFO.

PSA contract type	**Contract length**
Agroforestry systems	5 yrs.
Natural regeneration	5 yrs.
Forest protection	10 yrs.
Reforestation	10-16 yrs.

Because properties can be under PSA contracts multiple times, it is possible that there would be some duplication of areas within the dataset. A partial examination of potential overlap between properties revealed that most cases of overlap were margins of properties, likely an effect of spatial data collection, and did not involve more than 0.3% of the area examined for overlap in any of the examined map pairs. Because of this, all contracts with complete data were kept in the dataset.

3.2.5. Interpretation of carbon maps and parameters

Five maps of carbon stocks for Costa Rica, based on the REDD+ historical series of land cover maps and the FREL tool, were used as the base for all quantitative analyses (Figures 5-8). In these maps, each pixel is assigned a carbon value based on the type of land cover (classified according to the methodologies described in section 3.2.1.1) and carbon densities of each type of land cover (Table 3). These maps allow for visualization of areas of highest and lowest carbon stocks in Costa Rica. Some of the areas with large carbon stocks include several mountain ranges oriented northwest to southeast through the middle of the country, especially the southeastern region. Some of the areas with the lowest carbon stock include croplands and grasslands near the coasts of the country and urban areas in the center of the country.

These maps and the changes between them provide the basis for examining changes in carbon stocks over time. In Figures 5-8, each PSA contract is visualized at the year of the start of the contract as a polygon. Adding the carbon in each pixel that is within a given PSA contract polygon provides a measurement of the **carbon stock (tCO_2e)** contained in that PSA contract at that point in time. When comparing contracts or groups of contracts with different **areas (ha)**, values for **carbon density (tCO_2e-ha)** are used for normalization.

Measuring the carbon stock in each PSA contract during each point in time represented by a carbon map provides a time series of carbon stock measurements for each property in the PSA program. Because the contract start year and length varied throughout the PSA contract dataset and have varied during the program, the areas of individual contracts have a combination of carbon measurements before, during, and after the contract, providing the base for analyses of changes in carbon in the PSA program over time.

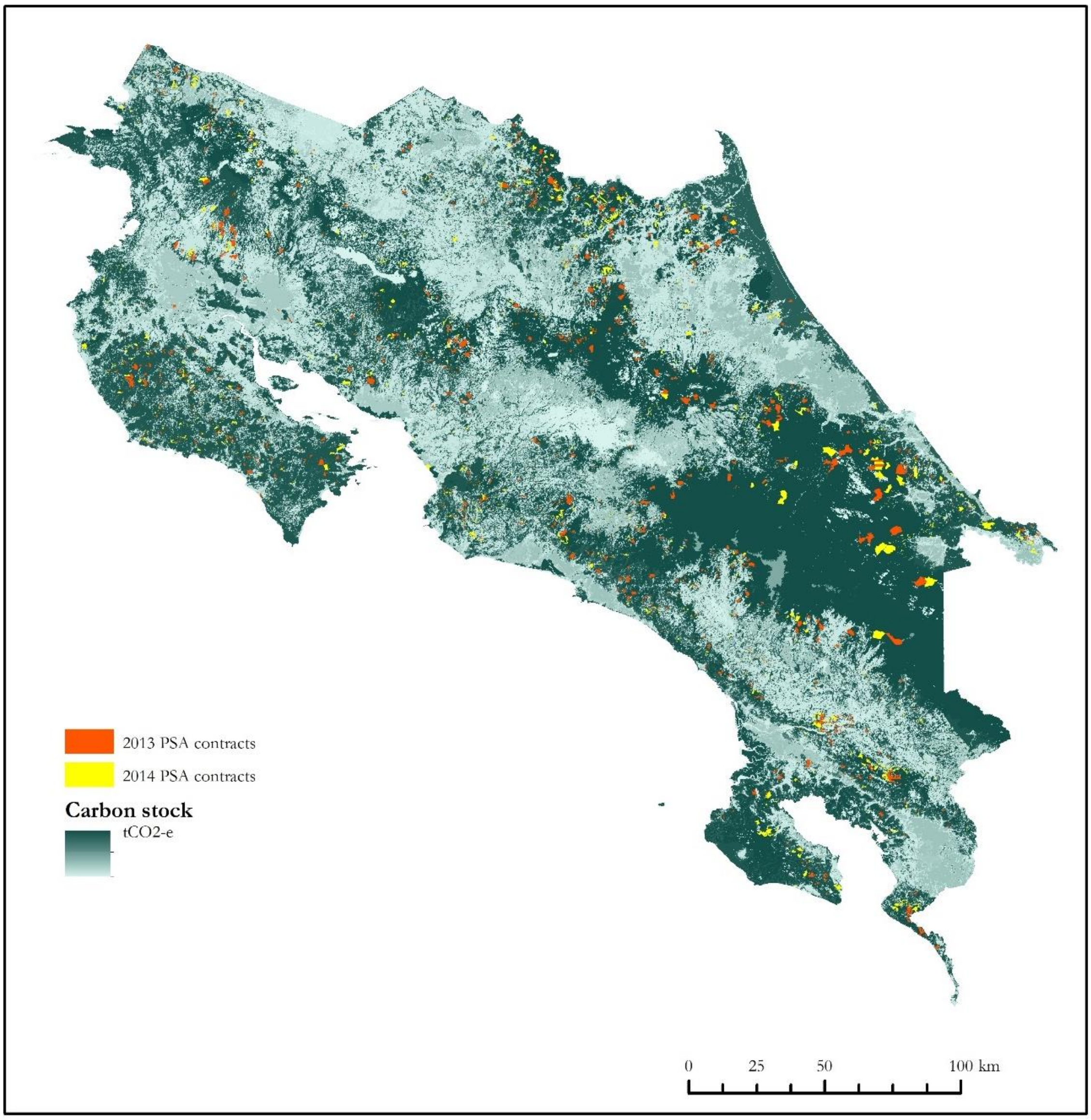

Figure 5. Map of carbon stock in 2013 in Costa Rica with the PSA contracts granted 2013 and 2014.[9]

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[9] Created by author using data from REDD+ and FONAFIFO.

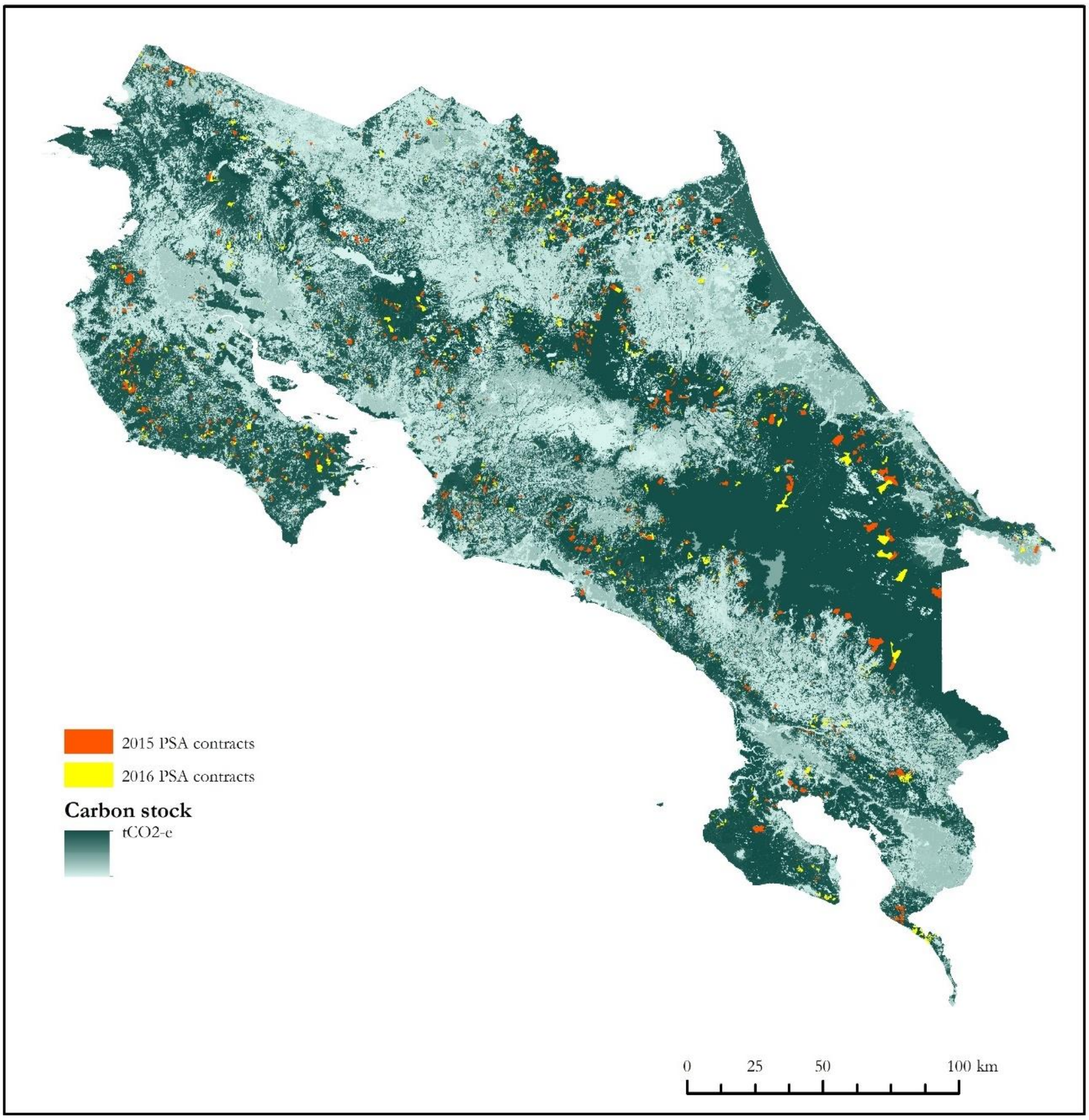

Figure 6. Map of carbon stock in 2015 in Costa Rica with the PSA contracts granted 2015 and 2016.[10]

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[10] Created by author using data from REDD+ and FONAFIFO.

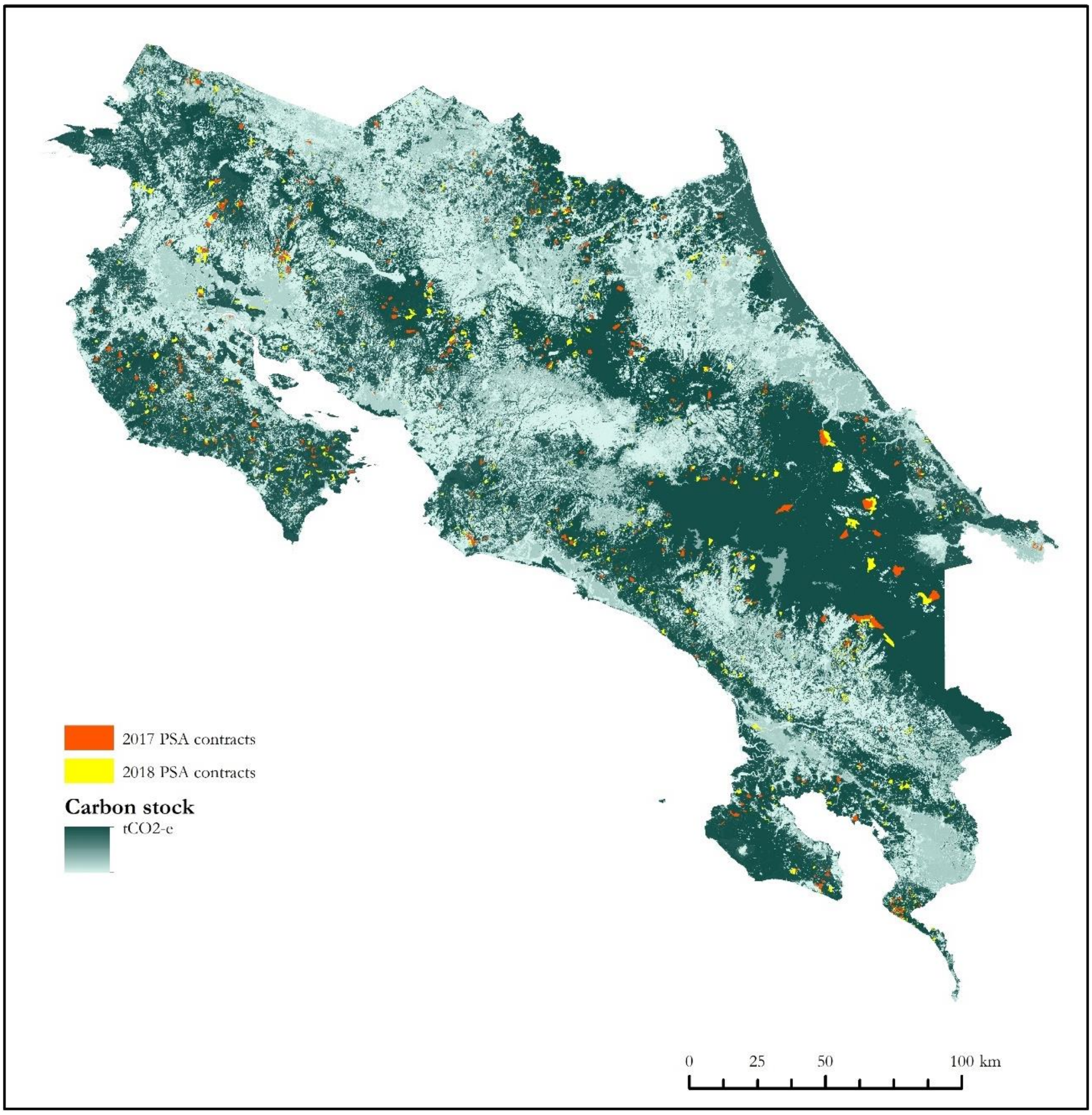

Figure 7. Map of carbon stock in 2017 in Costa Rica with the PSA contracts granted 2017 and 2018.[11]

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[11] Created by author using data from REDD+ and FONAFIFO.

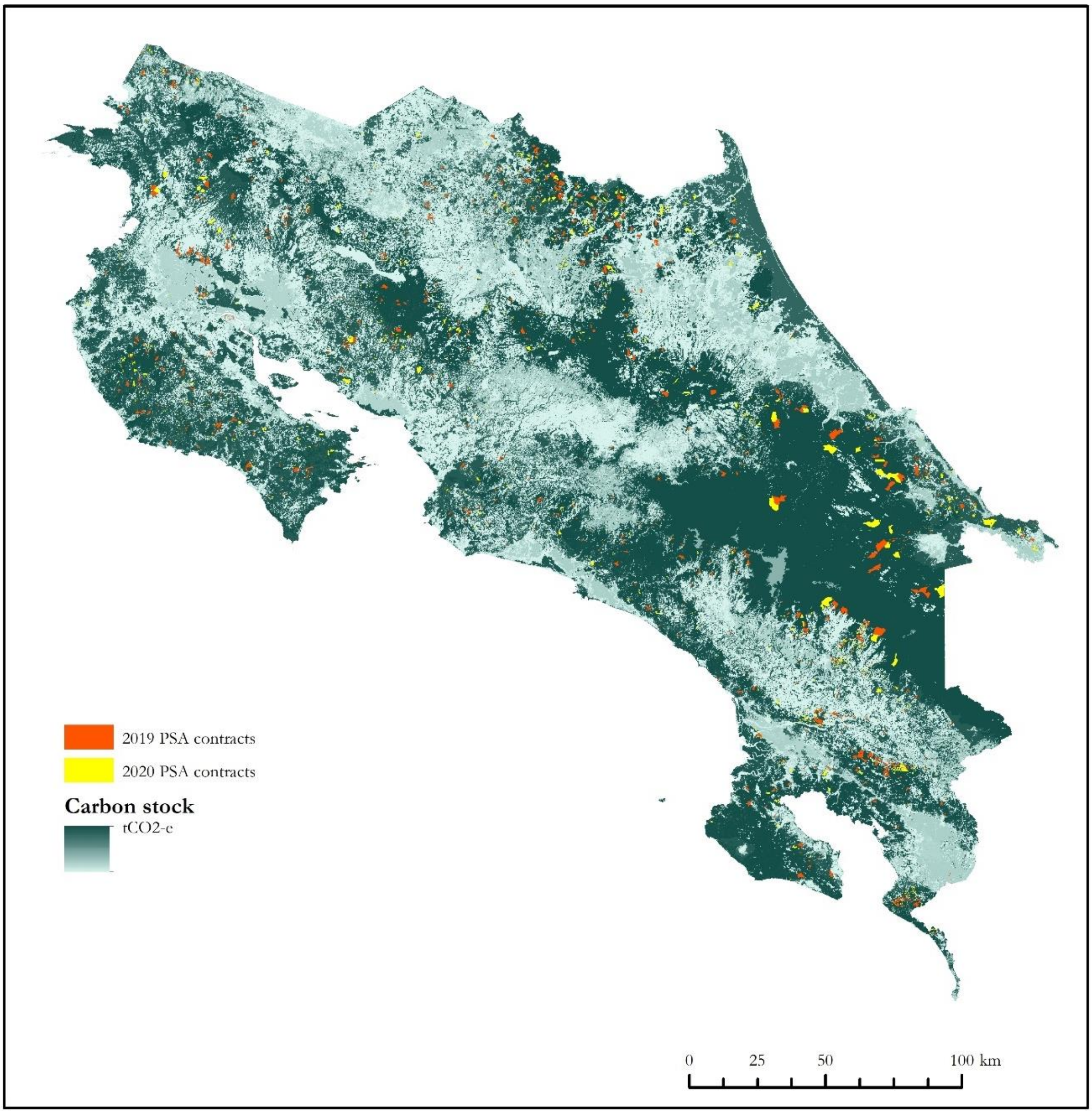

Figure 8. Map of carbon stock in 2019 in Costa Rica with the PSA contracts granted 2019 and 2020.[12]

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[12] Created by author using data from REDD+ and FONAFIFO.

4 Results

In this section, trends from the PSA program as a whole are presented and interpreted in section 4.1., while trends in carbon stocks in relation to program design features like spatial targeting and contract type are presented and interpreted in section 4.2.

4.1. Trends in carbon stocks in the PSA program 2012-2020

Trends that cover the entire PSA program reflect the effects of the entire program design during that time, but also many factors external to the management of the program. While this makes it challenging to attribute particular trends to a given management intervention or other relevant factor, it can provide some indication of the effects of all of the management strategies combined, especially considering that different management decisions may have different or even contradictory goals (Mickwitz, 2003).

4.1.1. Carbon stock and density

Each year, the PSA program has received applications and granted a new set of contracts with landowners for provision of ecosystem services over a certain period of time (the length of contracts by contract type can be found in Table 6). Each new cohort of contracts reflects both the pool of applications, but also the criteria used to prioritize granting of contracts and other organizational priorities and constraints, for example, budgetary constraints.

The number of new PSA contracts granted each year between 2012 and 2020, each of which represents a plot of land contracted to provide ecosystem services, ranged from around 600 to 1,250. The total area of land under new contracts for each year ranged from about 35,000 ha to 70,000 ha (Table 7). The total carbon stock in the new contracts is shown in Figure 9 and the carbon density of each cohort of new contracts is shown in Figure 10.

Table 7. PSA contracts granted per year, the area (ha) within the new contracts, and carbon stocks (tCO_2e) in the new contracts in the year granted.

	Number of contracts granted	**Area (ha)**	**Carbon stock (tCO_2e)**
2012	1,230	68,577.68	22,828,947.85
2013	1,243	68,245.23	23,553,830.30
2014	942	49,632.66	16,774,923.62
2015	1,021	69,841.06	24,382,311.58
2016	784	48,830.79	16,886,987.09
2017	629	45,280.50	15,944,469.41
2018	666	48,079.13	16,555,509.77
2019	737	51,952.52	18,362,755.36
2020	603	35,856.09	12,576,245.18

Total carbon stocks of cohorts were calculated as a sum of the carbon found within each PSA contract granted in that cohort. The total carbon stock in each cohort of new contracts does not describe the total carbon stock in PSA contracts during that given year, since there are contracts granted in previous years that are also active at the time. However, the carbon in new contracts granted each year provides a snapshot of the land cover of properties entering into the PSA program and an indication of the management decisions that lead to those contracts being granted.

In new contracts granted each year between 2012 and 2020, the carbon stock in the 2015 contracts was the highest, at almost 25,000,000 tCO_2e, while the 2020 new contracts held the lowest carbon stock, at about 12,500,000 tCO_2e (Figure 9). The general trend is a decline in total carbon stock in new contracts during this period. Since the number of contracts and total area in contracts also decline during the period, this may reflect budgetary constraints or other management decisions that result in funding of fewer contracts.

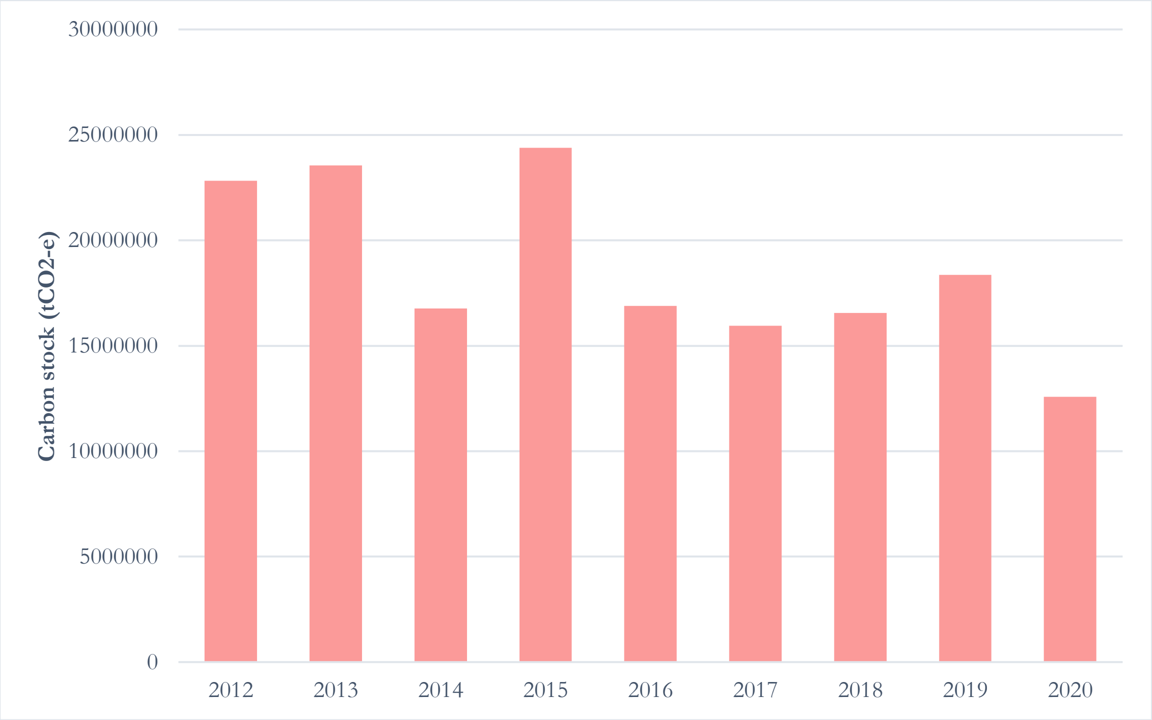

Figure 9. Total carbon stock (tCO_2e) in new PSA contracts per year 2012-2020.

An interesting juxtaposition is that, while carbon stocks in cohorts of new contracts entering the program decline between 2012 and 2020, the carbon density of those same cohorts of properties increases during that time (Figure 10).

The carbon density of a given area is a representation of the proportion of different types of land cover in that area. In this case, since the carbon density of the new properties in the PSA program is generally increasing year to year, this means that more carbon dense land cover, such as primary forests or older secondary forests are being represented more in more recent years of the program.

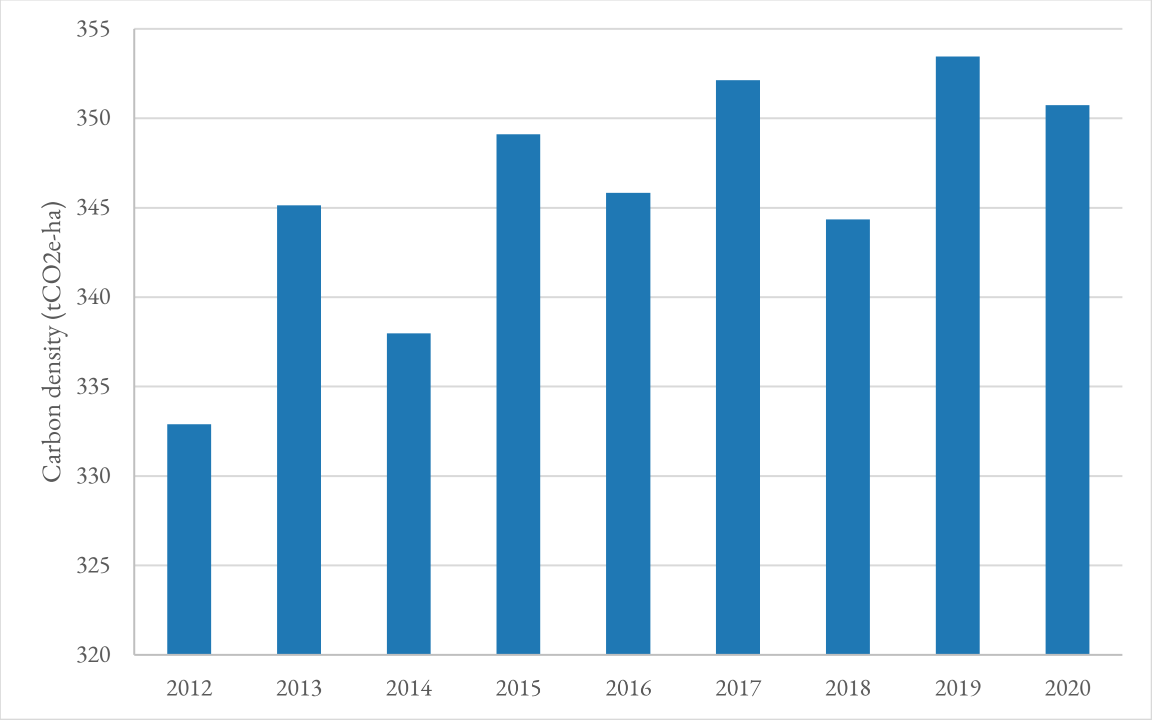

Figure 10. Carbon density (tCO$_2$e-ha) of new PSA contracts each year 2012-2020.

4.1.2. Strategic goals on mitigation of greenhouse gas emissions

While exploring trends in carbon stocks in the program as a whole provides an indication of the outcomes of the implementation and goals of the program, as well as relevant external factors, the PSA program also has explicit goals regarding provision of ecosystem services.

FONAFIFO's 2015-2019 strategic plan, which would be the institutional planning document applicable to over half of the contract years included in this study, did not have quantitative goals for ecosystem service provision, but did have a goal of determining the GHG emissions mitigation provided by properties with active PSA contracts (Fondo Nacional de Financiamiento Forestal, 2015). The achievement of this goal is not one that can be evaluated with measurements of carbon, but the addition of baseline values to the quantitative goals on ecosystem service provision in the following strategic plan is evidence that this goal was at least partially met.

The 2020-2025 strategic plan includes two quantitative strategic goals for ecosystem services: 115,000,000 tCO$_2$e in all properties with active contracts per year and 1,400,000 tCO$_2$e sequestered by the active agroforestry, natural regeneration, and reforestation contracts each year (Fondo Nacional de Financiamiento Forestal, 2019). The variation in the length of contracts, which can be up to 10-16 years, means that measuring the carbon stock of all properties with active contracts in a given year could require adding contracts that were granted a decade or more before the target year. For example, the active contracts during the year 2020 could include contracts that were granted in 2010 or earlier. Since the oldest cohort of PSA contracts in the data set used was contracts beginning in 2012, it was not possible to have data for all active contracts for any target year of this study. However, during 2019 and 2020, which would have the most complete data, total carbon stocks in active contracts were already above the goal (Figure 11). The baseline that was included in the strategic plan (121.573.982 tCO$_2$e), which does not include a source, provides additional evidence that the goal has been met in the past as well, although more conservatively.

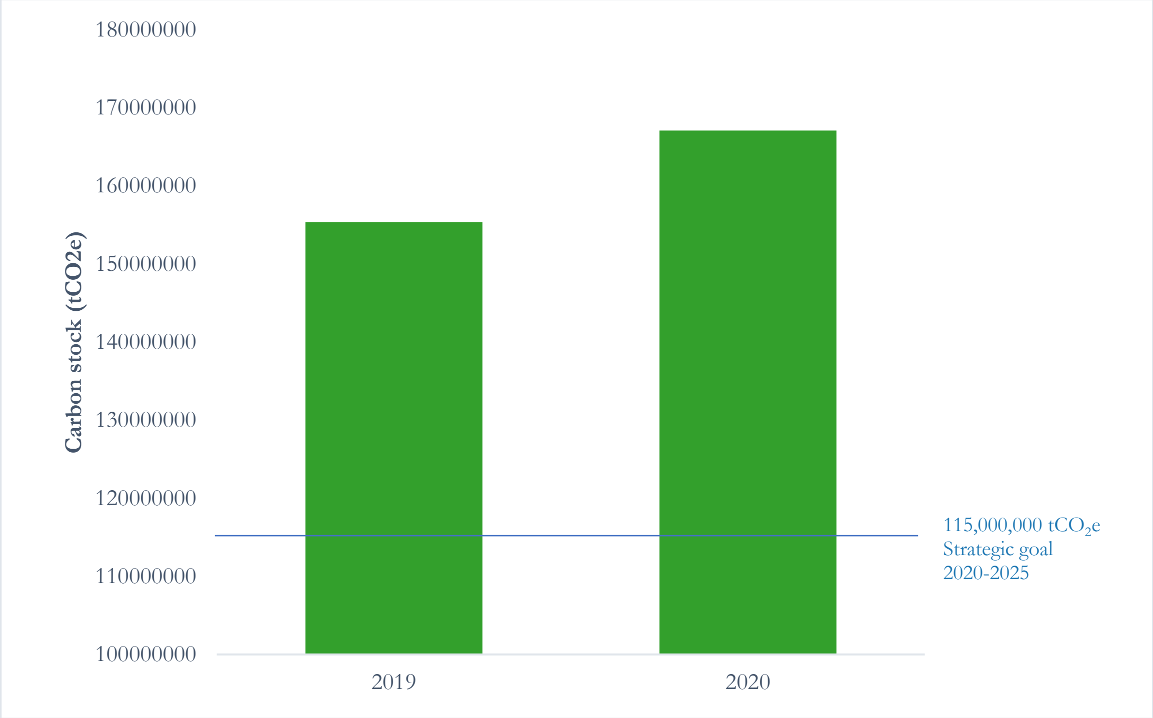

Figure 11. Total carbon stock ($tCO_{2}e$) in active PSA contracts during 2019 and 2020 compared to the FONAFIFO strategic goal for 2020-2025.

The second goal of 1,400,000 tCO_2e in sequestration by the agroforestry, natural regeneration, and reforestation active contracts is not possible to evaluate fully because of limitations in the data on enhancement and degradation of forests over time. However, for this goal, the baseline in the FONAFIFO 2020-2025 strategic plan is 1,455,108 tCO_2e, which is also above the goal and suggests that the goal has been met before.

4.2. Trends in carbon stocks by program design features

4.2.1. Spatial targeting and prioritization

Since 2010, which includes the entirety of the period of time covered in this study, the PSA program has targeted specific areas of Costa Rica to prioritize in the granting of contracts (Sánchez-Chaves & Navarrete-Chacón, 2017). These priority areas target provision of ecosystem services, although little information is available about how they are determined. When considered together as one priority area, where properties applying within the area would be prioritized for granting of contracts, more than half of the country falls within a priority area. Comparing the carbon stock in priority areas to non-priority areas as a baseline can provide an indication of whether spatial targeting is effective in prioritizing areas that have greater carbon stocks. The prioritization areas for the 2022 PSA had a higher carbon density than areas that were not prioritized, at around 250 tCO_2e-ha compared to the baseline of 150 tCO_2e-ha (Figure 12). This suggests that the 2022 prioritization criteria did prioritize areas with higher carbon stocks.

The specific prioritization criteria used for spatial targeting in the PSA program include protected areas, indigenous territories, biological corridors, conservation priority areas, and watersheds. Comparing the carbon stocks of the individual priority areas allows for comparison of the effectiveness of each priority criterion in targeting areas of higher carbon stocks. Carbon densities of the different environmental prioritization criteria for the 2022 PSA program varied, with indigenous territories, protected areas, and important areas for conservation having densities of over 300 tCO_2e-ha and areas for watershed protection and biological corridors having less than 250 tCO_2e-ha (Figure 12). This indicates that indigenous territories, protected areas, and important areas for conservation were better criteria at targeting areas of higher carbon stocks, although each priority area individually was had a higher carbon density than the baseline of non-priority areas (Figure 12). This may indicate in part the potential land uses of the different priority areas because of the different management restrictions associated with these criteria; for example, protected areas are typically managed to exclude low carbon density land uses like urban areas, whereas biological corridors are managed to optimize connectivity, especially in degraded landscapes.

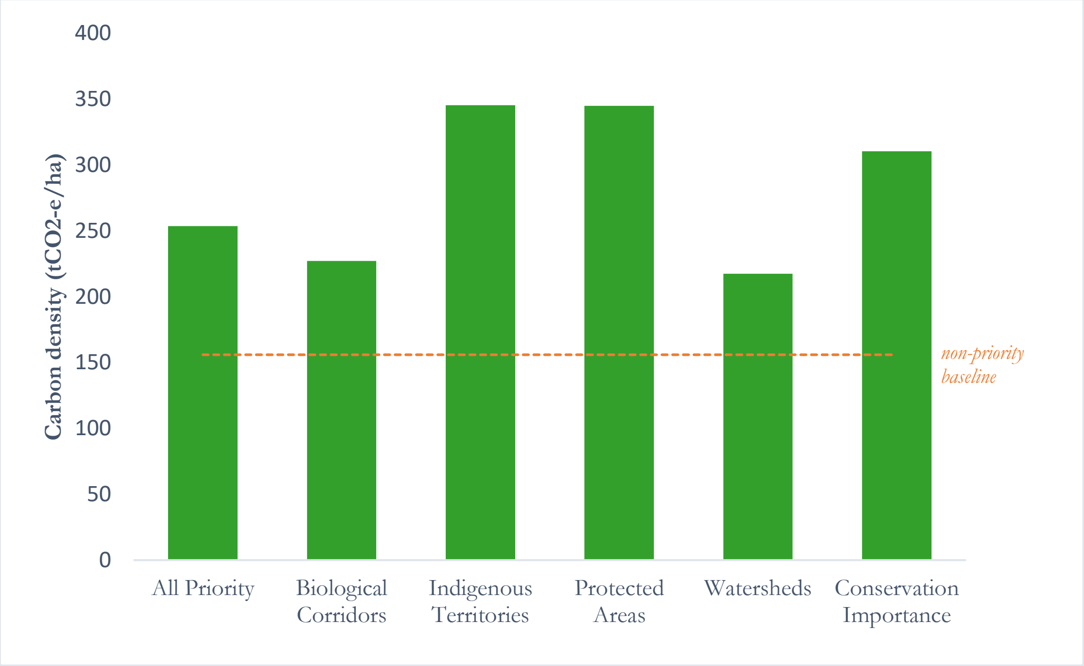

Figure 12. Carbon density (tCO_2e-ha) of all priority areas together and each priority area individually of the prioritization areas for 2022 PSA contracts compared to all areas not prioritized for PSA contracts (non-priority baseline).

An important consideration in understanding these results is that the prioritization criteria used for spatial targeting are not the only criteria involved in prioritizing applications for granting contracts. Qualification criteria such as property size and land use and also socioeconomic prioritizations such as gender or a national social development index contribute to determining the prioritization of applications in addition to the spatial targeting criteria (Sánchez-Chaves & Navarrete-Chacón, 2017). A second consideration related to the spatial targeting criteria is that there are spatial overlaps between priority areas, so some applications may be prioritized more than others because of meeting multiple prioritization criteria.

4.2.2. Contract types

In addition to prioritization, another feature of the PSA program design that provides opportunities to influence the provision of ecosystem services is the contract type. The PSA program features several contract types with different contract lengths and expectations regarding land use. The contract types in the PSA program during 2012-2020 were forest protection, forest management, agroforestry systems, mixed systems, reforestation, and natural regeneration, as well as some sub-categorizations that were not included in this study. While originally these contract types were separate, they are now broadly separated in two categories, one where the expectation is maintaining forest cover (forest protection) and one where the expectation is recovery of forest cover (agroforestry, natural regeneration, reforestation, and forest management).

Because the land cover of properties at the start of these two types of contracts could be more mixed in the case of contract types aimed to increase forest cover (e.g., in agroforestry contracts the land cover might be mostly croplands), two baselines are used to compare the trends in carbon stocks for different contract types. The forest baseline is composed of forests in all priority areas excluding all PSA contracts granted in 2012-2020 and can be used as a point of comparison for the forest protection contract type. The mixed landscape baseline is composed of all priority areas excluding all PSA contracts granted in 2012-2020 and can be used for the contract types that aim to increase forest cover.

For all contracts in the different PSA contract types 2012-2020, the carbon density was nearly 350 tCO_2e-ha, well above the mixed landscape baseline and just below the forest baseline (Figure 13). The high carbon density at the beginning of contracts compared to the rest of the landscape within priority areas could be related to a high proportion of forest protection contracts and could also be a reflection of the results of the prioritization criteria.

For the individual contract types, the carbon density at year one varied, with forest protection and forest management having carbon densities over 300 tCO_2e-ha, mixed systems and natural regeneration having carbon densities between 250 and 300 tCO_2e-ha, and agroforestry systems and reforestation containing less than 250 tCO_2e-ha (Figure 13). The forest protection contract type exceeded the forest baseline and the forest management contract type exceeded the mixed landscape baseline, while the other contract types had lower carbon densities than the mixed landscape baseline. While the difference in carbon densities between contract types is quite large, where forest protection contracts had more than double the carbon density of agroforestry systems in the first year of the contract, this may highlight the important difference in the expectation for land use change for these contract types.

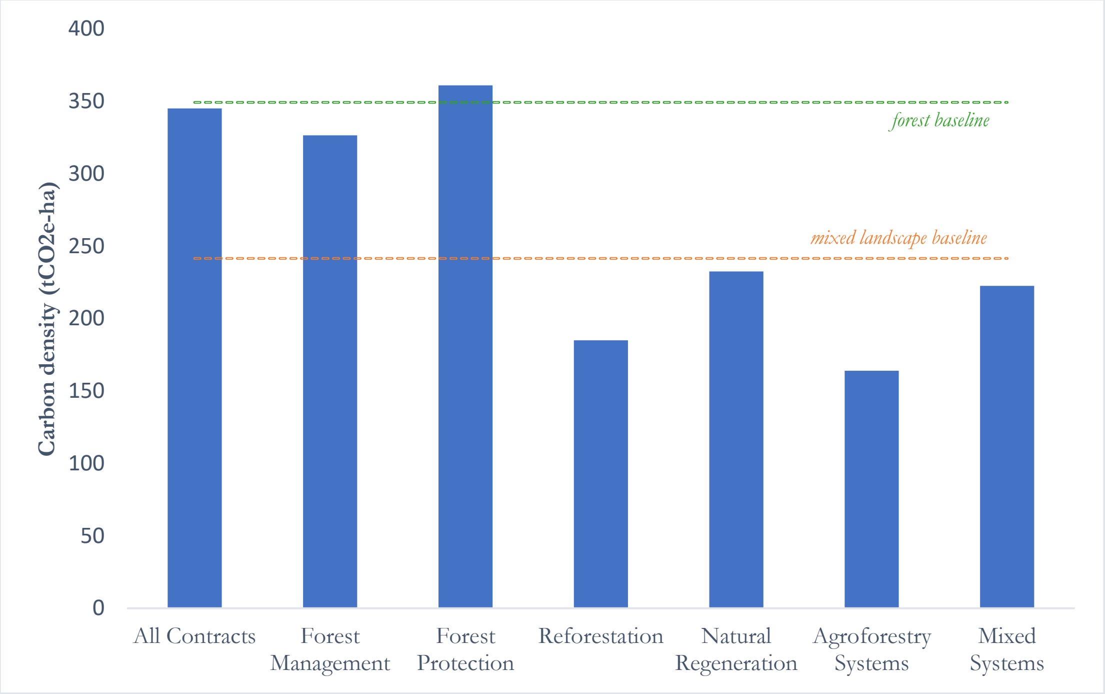

Figure 13. Carbon density (tCO2e-ha) in the first year of the contract of all contracts and by PSA contract type for 2012-2020 compared to a mixed landscape baseline and a forest baseline.

Since the land cover under PSA contracts could be expected to change during the program, as it would be if the aim of a given contract type is to increase forest cover, it is interesting to not only observe carbon density but also the change in carbon stocks. Because the length of many of the contracts goes beyond the data set of PSA program contracts 2012-2020, it is not possible to replicate this analysis using the last year of the contract, since in 2020 many of the contracts were still active. However, an estimate of the change in carbon stocks per year per hectare can be calculated for all contracts in the program for at least two years, this indicates, to a certain extent, carbon sequestration during the PSA program. It takes into account the changes in land cover seen between the first and last years under contract, regardless of whether the contract is finalized.

For all contracts together, the change in carbon stocks is greater than the change in carbon stock in the mixed landscape baseline and the forest baseline, meaning that as a whole, all the 2012-2020 PSA contracts gained more carbon per year than the landscape baselines (Figure 14). Taken individually, the change in carbon in the forest protection contract type was below the forest baseline while the change in carbon for all other contract types was above both the forest baseline and the mixed landscape baseline. This suggests that the forest protection contract type as a whole was not gaining more carbon than other forests in priority areas, but that the other contract types were gaining more carbon than the landscape baseline. Since forest protection is not intended to increase forest cover but the other contract types are, this result is consistent with the aim of the contract types. However, it is worth noting that there is still variability between the rate of change in carbon of different contract types. For instance, the reforestation contracts gain over 2.5 tCO2e-yr-ha while natural regeneration contracts gain a bit under 1.5 tCO2e-yr-ha. This variability could be partly due to the type and speed of land use change in each contract type.

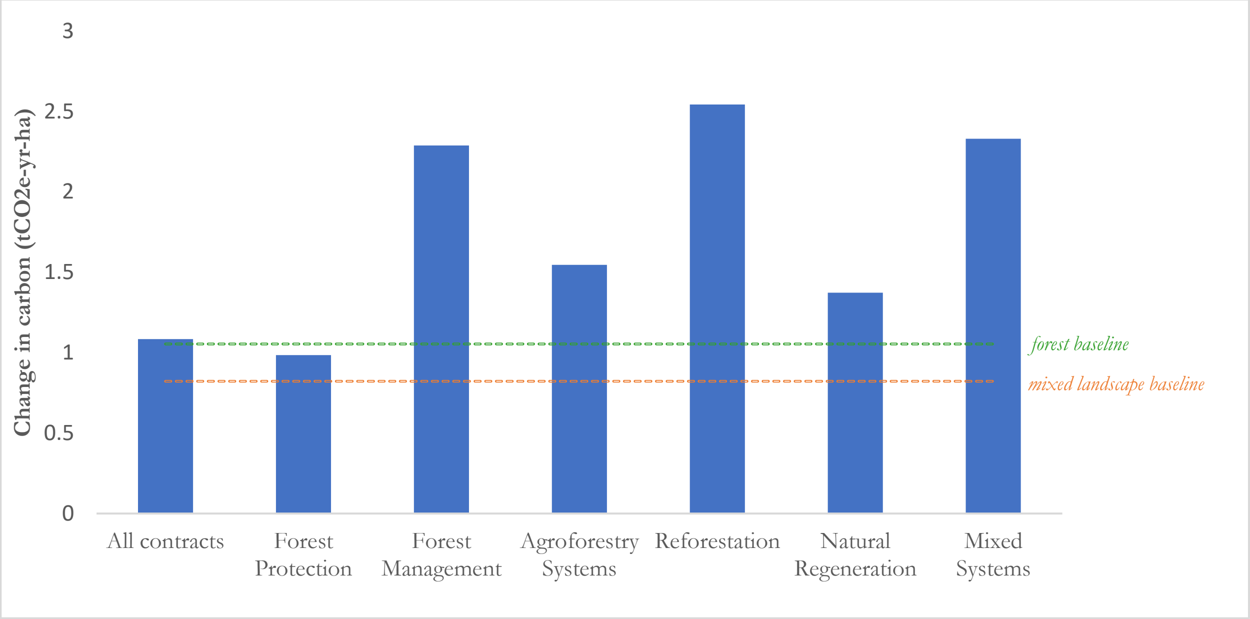

Figure 14. Change in carbon stock (tCO2e-yr-ha) during the contract of all contracts and by PSA contract type for 2012-2020 compared to a mixed landscape baseline and a forest baseline.

5 Discussion

5.1. All PSA program design strategies had higher carbon stocks or sequestration than baselines

Each goal, priority area, and contract type explored in this study was associated with either higher carbon stocks or change in carbon stocks than the goals or baselines that they were being compared to. This provides evidence that the PSA program was effective at delivering GHG emissions mitigation through carbon stocks.

However, there were also contract types that were only above the baseline either on carbon stock at the beginning of the PSA contract or rate of change in carbon stock. Additionally, even within priority areas and contract types that were above the relevant landscape baseline, there was variability. Several of the environmental evaluations of the PSA program explored in section 2.2 also found that different spatial or temporal scopes or different methodologies resulted in different assessments of effectiveness or additionality (Calvet-Mir et al., 2015; Legrand et al., 2013). Given the range of different carbon densities by priority area or contract type in this study, it is readily apparent that very different outcomes would be possible, especially in evaluations performed over smaller spatial or temporal scales.

5.1.1 Strategic goals and program trends

With goal setting and planning, the most relevant goals in program strategic plans related to the provision of environmental services were met. The goal of 115,000,000 tCO_2e in all active contracts in the program per year was met and exceeded for both 2019 and 2020. However, in conjunction with the observed trend of decreasing number of contracts and total carbon stock in new cohorts of contracts, the same goal could become more difficult to achieve in future years. Total carbon stock in years 2019 and 2020 included active contracts from the years with the highest number of contracts, which will no longer be the case in 2024 and 2025, which have the same carbon stock goal in the 2020-2025 strategic plan (Fondo Nacional de Financiamiento Forestal, 2019). Additionally, if budgetary constraints or changes in sources of income like the tax on fossil fuels made it more difficult to fund the same number of contracts each year, this could also make it more challenging to meet the goal in the 2020-2025 strategic plan.

While there were some estimates of carbon sequestration, these could not be applied to assessing the goal in the 2020-2025 strategic plan on carbon sequestration. However, the trend in increasing carbon density of new PSA contracts may suggest that properties with more forest or more mature forest are being selected, which could also make it more challenging to meet goals on carbon sequestration.

5.1.2 Spatial targeting and prioritization

Regarding spatial targeting for prioritization of contracts, the total prioritization area was effective at prioritizing higher carbon stocks. Of the different prioritization criteria, protected areas, indigenous territories, and areas of conservation importance were the most effective at targeting areas with high carbon densities. In comparison, watersheds and biological corridors were less effective at targeting high carbon density areas, although all were more carbon dense than the non-priority baseline.

5.1.3 Contract types

When considering all contract types together, PSA contracts had both higher carbon density at the beginning of contracts and a higher rate of growth in carbon stocks than the mixed landscape baseline and a slightly higher rate of growth than the forest baseline as well. This indicates that the trend is that properties in the program stored more carbon than the landscape around them and also added to their carbon stocks more quickly.

In comparing the carbon densities of different contract types using contracts in the first year of the PSA program, forest protection and forest management were the contract types with the highest carbon densities and were also the two contract types that were higher than the relevant baseline. Reforestation, natural regeneration, mixed systems, and agroforestry systems were contract types with lower carbon densities than the mixed landscape baseline, with agroforestry systems being the least carbon dense.

In comparing the rate of increase in carbon stocks of the different contract types, reforestation, mixed systems, and forest management had the highest rate of carbon stock growth, followed by natural regeneration and agroforestry, all of which were higher than the mixed landscape baseline and also the forest baseline. In contrast, forest protection had a lower rate of change in carbon stocks than the forest baseline. One important consideration in the data on sequestration is that there were limitations in the ability to measure enhancement or degradation of forests, leaving out two of the ways that land use and carbon stocks could change during the PSA contracts.

An interesting result to note is that forest management is the only contract type that exceeds baselines both on carbon density and also growth of carbon stocks. However, this is one of the contract types with the fewest contracts, so this may be due to a lower sample size. This is an area in which there is also great variability, as some contract types had a disproportionate number of contracts compared to others.

5.2. Multiple policy goals result in multiple tradeoffs

Although the contract types and priority areas that were associated with lower carbon stocks or lower sequestration could be examples of less effective program design or management strategies, they may also indicate tradeoffs between program goals. Evaluating the carbon stocks in the PSA program under different conditions can provide valuable information with which to assess the effectiveness of different strategies aimed to target the provision of GHG emission mitigation through carbon storage. However, this policy goal is not in isolation and multiple policy goals and strategies can interact to produce different results.

The low carbon densities of reforestation, natural regeneration, and agroforestry contract types, in which recovery of forest cover is an expected outcome, may not indicate an ineffective mechanism to prioritize high carbon stocks, but a goal of carbon sequestration, which would be expected from recovering forest cover. And conversely, the low rate of growth of carbon stocks in the forest protection contract type may indicate effective selection of mature forests for protection. The links between these contract types and carbon sequestration or other policy goals could be explored to better assess whether these contract types are effective in achieving other goals.

The low carbon densities of biological corridors and watersheds could indicate separate tradeoffs between carbon and other ecosystem services. The PSA program targets four ecosystem services, and some prioritization criteria may target certain ecosystem services better than others. For example, biological corridors have the goal of providing connectivity, often in degraded or fragmented landscapes (low carbon stocks), for protection of biodiversity, which is one of the ecosystem services in the PSA program. Hydrological services, for which protection of watersheds can be important, is another of the ecosystem services in the PSA program. Further research could explore the links between goals and outcomes in different ecosystem services, as targeting may not always be effective. Legrand et al. (2013), in an assessment of the PSA program, found that the link between goals and outcomes was weak for water, but strong for biodiversity and carbon.

Lastly, while the PSA program does have goals for ecosystem service delivery, as one of the main goals of the program, it also has socioeconomic goals and goals for landscape change built into the program as well. Environmental and socioeconomic goals can also interact in complex ways and many evaluations of the PSA program address both to better understand the different factors influencing the outcomes of the program.

5.3. Monitoring of ecosystem services is still a challenge

Data on ecosystem services over large spatial and temporal scales at a relevant resolution is difficult and costly to generate and maintain up to date. The data sets used in this study to create maps of carbon stocks that are comparable over a span of almost 35 years were created within the past 5-10 years for the purpose of participation in REDD+ activities and have been created and updated in large part by consultants, which can be an additional strain for institutions. The National Forest Inventory, created with data taken in 2013 and 2014, cost nearly 1 million USD and provided a portion of the data on carbon densities that was compiled in data sets used to create the maps in this study (Emanuelli et al., 2016).

Even with the high cost of generating data at that scale, the next National Forest Inventory is expected to be carried out during 2020-2034 to provide updated data on plots measured previously and to assess new plots as well (Aguilar Porras & Fallas Gamboa, 2020). This inventory is expected to use methodologies that make it relevant to multiple institutions in the environmental sector in Costa Rica, which is a step toward improving data sharing between institutions.

An additional layer of complication in the creation and use of large-scale data sets on ecosystem services is related to compatibility of the data. If data collection or creation of specific data sets is not carried out with all the potential uses in mind, data management processes like normalizations or filtering of data can be done afterward but may generate uncertainties or loss of data. These challenges were present in the methodologies used by consultants to create the data sets used in this study and also in the process of adapting the data sets from FONAFIFO and the REDD+ Secretariat to be used for evaluating the PSA program. Likely in part because of these difficulties, other assessments of the PSA program I reviewed have not evaluated the program at the temporal and spatial scales in this study. The scale and the evaluation of relevant program management strategies make this study a relevant tool for PSA program management, especially since monitoring of ecosystem service provision is not a regular part of the PSA program.

Many of the limitations of this study stem from the challenges with working with the type and scale of data used. The main uncertainties coming from the data sets used are summarized in section 3.2.2. The temporal scale of the study was limited by the PSA contract data set beginning in 2012 and the most updated publicly available REDD+ land cover map being the 2019-2020 map. The long duration of some PSA contracts and limited information about the real length of each contract made it challenging to aggregate data on all active contracts at a given point in time, which would allow for more in depth analyses of changes over time in the program.

Lastly, the combination of a time lag in the appearance of forests in land cover maps and the short length of some PSA contracts make it difficult to observe changes in carbon stocks during the contract duration. A clearer understanding of when you could expect to observe changes in land cover, especially in the contract types that aim to increase forest cover, could make it easier to interpret the changes seen over time. In short contracts, for instance, some of the effects of land use changes during the PSA contract may be most visible after the end of the contract. Similarly, a more nuanced approach to creating baselines could provide better points of comparison for specific contract types or priority areas.

6 Conclusions

In an established and well-regarded environmental program like the Costa Rican PSA program, it is important to evaluate the effectiveness of policy design and management strategies in achieving the program's goals. One of the key expected outcomes of the PSA program is delivery of ecosystem services; however, the program does not systematically monitor the provision of the four ecosystem services covered in the program.

Most evaluations of the PSA program have been conducted with limited spatial and temporal scales, but recent data sets on carbon densities and land cover created for REDD+ activities provide a time series of comparable carbon stock data at a national level. Carbon stock data were used to evaluate the effectiveness of PSA program design mechanisms in providing GHG emissions mitigation services through carbon stocks. Mechanisms evaluated were goal setting and planning, spatial targeting and prioritization, and categorization of contract types; each was effective in having higher carbon density or growth in carbon stocks than baselines.

The measurable stated goals were met, although meeting them may become more challenging in the future if a trend of fewer contracts and smaller contract areas continues. In spatial targeting, all priority areas were more carbon dense than non-priority areas, but protected areas, indigenous territories, and conservation importance were most effective at targeting areas of higher carbon density. In contract types, forest protection and forest management contracts had higher carbon densities at the beginning of the contracts than baselines, while agroforestry systems, reforestation, mixed systems, natural regeneration, and forest management contracts had higher rates of increase in carbon stocks than baselines.

Scenarios that resulted in lower carbon densities or growth rates may reflect tradeoffs with other ecosystem services or with other goals of the program. Further research on carbon and data on all four ecosystem services and socioeconomic goals would allow for better information for how to target relevant goals with management decisions.

6.1. Policy recommendations

While there are many ways that better information about ecosystem services can improve environmental policies like the PSA program, the following are some of the most relevant from this study for the PSA program, which could also be important for many other PES programs as well.

Investigate weakest links to ecosystem service provision

Since there were several scenarios observed in results that did not have high carbon stock or density, these could be investigated further to assess its effectiveness. For example, the agroforestry systems contract type could be a key one to examine more carefully to understand the policy goals it helps achieve. One factor that distinguishes this contract type are that it had the lowest carbon density of all scenarios measured except for the areas not prioritized by the program at all. Also, the contracts are for 5 years, which is the shortest contract length and may not be long enough to benefit from changes in forest cover or management practices.

Implement internal monitoring of ecosystem services

Although there are still many challenges in generating long-term and large-scale data on ecosystem services, incorporating monitoring of ecosystem services into the PSA program would allow for more nuanced evaluation of the effects of management decisions, including assessment of possible outcomes before making changes to program design. Monitoring of ecosystem services would also allow for improved goal setting and identifying of program-scale trends.

Additionally, data on PSA contracts typically used for monitoring compliance could also provide a tool to also measure ecosystem services with some changes to enhance compatibility like identifying when properties are in the program multiple times.

Share institutional resources to maximize informative tools

While monitoring of ecosystem services can be resource intensive, better integration with other institutions to share data could free up resources for other program activities or broadening the scale of monitoring activity. For example, data from the National Forest Inventory could serve as a partial base for monitoring carbon stocks and biodiversity.

6.2. Future research

This study provides a quantification of one of the ecosystem services in the Costa Rican PSA program, which is not information produced internally in the program. Additionally, it looks at trends in carbon stocks related to management decisions in the program, which can provide information about the effectiveness of the program design and could be used to improve the program. Lastly, the data set created with over 7,500 contracts and carbon measurements in a time series for each contract could be used to evaluate the PSA program using other criteria.

There are many other criteria that can be used to evaluate PES programs, many of which could be tested on a data set of the scale used in this study. For example, data on the changes in carbon stocks of entire properties, rather than just the sections under PSA contract, could be used to measure leakage, the impacts that a PES program can have on areas that are outside its geographic scope. In addition, permanence, or the longevity of program outcomes beyond the end of contracts, has been studied very little because most PES programs are relatively recent. A long-term dataset on PES contracts like the one used in this study could be used to assess permanence if the length of contracts were clearer.

While carbon data has become more available because of its role in climate change mitigation, measuring other ecosystem services that may be underrepresented in monitoring efforts and therefore in targeting is important to ensure continuity in the provision of important ecosystem services.

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