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Theoretical-empirical Article

The Impact of Payments for Environmental Services in the Atlantic Forest: A Geospatial Study

O Impacto de Pagamentos de Serviços Ambientais na Mata Atlântica: Um Estudo Geoespacial

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ABSTRACT

Objective: this study aimed at understanding the impact of payment for environmental services (PES) programs in relation to environmental indicators in the Brazilian Atlantic Forest biome. **Theoretical approach:** the literary framework included three topics of discussion: payment for environmental services, program evaluation, and theory of change. In a broader way, the theme of evaluating programs in the agricultural area was articulated, considering the precepts of the theory of change. **Method:** geospatial data on land use, between 2016 and 2021, and amounts paid under the PES program with rural producers were collected to evaluate the impact on the increase or decrease in degraded and recovered areas. Data analysis included multivariate statistics, more specifically the comparison between groups and the relationship between variables through multiple linear regression. **Results:** the empirical results highlight that there is a significant difference in the increase in areas under recovery between producers who received PES values and producers not participating in this program. As for the types of PES, the one that pays for improvements in land use contributed most to the increase in the area under recovery. **Conclusions:** the study shows that evaluation methods for PES must be increasingly complex and measurable, as there are several possibilities for impacts depending on the objective of the program. The results are relevant to the theoretical, practical, and social spheres, in addition to helping to achieve the Sustainable Development Goals (SDGs).

Keywords: impact assessment; payment for environmental services; theory of change; geospatial analysis; Atlantic Forest.

RESUMO

Objetivo: este estudo buscou compreender o impacto dos programas de pagamento por serviços ambientais (PSA) em relação aos indicadores ambientais no bioma da Mata Atlântica brasileira. **Marco teórico:** o arcabouço literário contemplou três tópicos de discussão: pagamento por serviços ambientais, avaliação de programas e teoria da mudança. De maneira geral, articulou-se a temática da avaliação de programas na área agrícola, considerando os preceitos da teoria da mudança. **Método:** dados geoespaciais de uso de solo, entre 2016 e 2021, e de valores pagos em programa de PSA junto a produtores rurais, foram coletados para avaliar o impacto no aumento ou diminuição de áreas degradadas e recuperadas. A análise de dados contemplou a estatística multivariada, mais especificamente da comparação entre grupos e da relação entre variáveis através da regressão linear múltipla. **Resultados:** os resultados empíricos destacam que existe diferença significativa no aumento de áreas em recuperação entre os produtores que receberam valores em PSA e os produtores não participantes deste programa. Quanto aos tipos de PSA, aquele que paga por melhoria no uso do solo foi o que mais contribuiu com aumento da área em recuperação. **Conclusões:** o estudo evidencia que os métodos de avaliação para PSA devem ser cada vez mais complexos e mensuráveis, pois existem várias possibilidades de impactos conforme o objetivo do programa. Os resultados são pertinentes para as esferas teórica, prática e social, além de ajudarem no alcance dos Objetivos de Desenvolvimento Sustentável (ODS).

Palavras-chave: avaliação de impacto; pagamento por serviços ambientais; teoria da mudança; análise geoespacial; Mata Atlântica.

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INTRODUCTION

The issue of defending the natural environment is one of the most debated around the world today. It is considered essential for all speculative events regarding the future. Environmental valuations, within the scope of negative externalities, occur through economic instruments that assign prices according to scarcity and social costs, such as taxes, fees, charges for use, and market share mechanisms (Ferreira et al., 2021; Jack & Jayachandran, 2019).

According to the Organization for Economic Co-operation and Development (OECD, 2018), environmental goods (or services) are those whose purpose is to measure, prevent, limit, minimize, or correct environmental damage to water, air, and soil, as well as problems related to waste, noise pollution, and damage to ecosystems. Preventive policies with mechanisms that value the environment are present in the world economy.

The current mechanisms of environmental valuation follow three principles: (a) the attribution of values by use (user pays); (b) the attribution of values for the impediment of use in the case of environmental damage (polluter pays); and (c) the attribution of values for the protection of natural resources (protector-receiver), among which we highlight the principle of paying to those who protect the environment. The principle of a protector-receiver emerged in the United States as a way to mitigate the negative impacts of agricultural activities on watersheds, configuring the preventive policy of the so-called payments for environmental services (PES) (Pereira & Alves Sobrinho, 2017).

Currently, PESs are discussed worldwide and focus on water, carbon, biodiversity, and scenic beauty. PES is a relevant topic worldwide because it stimulates the recovery and protection of ecosystems and changes the relationships between the government and the landowners (Ruggiero et al., 2019; Wunder et al., 2020).

Therefore, PES is a mechanism capable of generating many benefits for all involved by ensuring a financial return for those who restore and conserve forests and landscapes when applied with governance, transparency, and legal certainty (WRI Brazil, 2021).

PES has become an environmental management tool as well as a business practice that prioritizes sustainability, such as environment, social, and governance (ESG), complementing policy tools that were previously largely focused on command-and-control measure (Ezzine-de-Blas et al., 2016; Lapeyre et al., 2015). However, the context in which most PES schemes operate is often characterized by high uncertainty in the accountability of environmental services due to the biophysical complexities associated with the relationship between land use and these services (Pascual et al., 2010).

According to Wunder (2007), as with any public policy program, it is necessary to have a secure idea of what would hypothetically happen without the PES program, that is, to build the counterfactual service baseline (Sills et al., 2006), to observe its efficiency. This is in line with the findings of Araújo (2019), who stated that environmental effectiveness is defined as the change in the provision of services induced by a program compared to what would happen in the absence of a PES intervention.

Therefore, evaluation is essential for improving the effectiveness and efficiency of conservation programs (Kleiman et al., 2016). Therefore, evaluating PES programs is a way of understanding how these policies impact the public involved (Bauchet et al., 2020; Rodrigues et al., 2021). In addition, the impact measurement is a gap observed by investors, entrepreneurs, and scholars, who seek to measure the impact and transformation generated considering the hypotheses prepared based on the theory of change (TC) (Sugahara & Rodrigues, 2019).

In this context, this study sought to understand the impact of the PES on several environmental indicators in the Brazilian Atlantic Forest biome, given its importance, as described below in the methodology section. For this purpose, geospatial remote sensing data in the region of this biome were analyzed. This understanding is necessary because the currently available PES project evaluation models are disparate and diverse, in addition to being heavily based on qualitative analyses, thus suggesting the need to quantify measurement data for such actions. The assessment quantification detects the impacts on the socio-environmental reality of adopting a scheme, about its counterfactual.

Therefore, according to, Costedoat et al. (2015) PES programs are not easily measurable, and the recent development of evaluation methods is essential for their counterfactual estimation. In addition, PSE actions are recent, and the evidence on their efficacy is still scarce and quite confusing (Araújo, 2019; Engel, 2016; Rodrigues et al., 2021). These schemes result from complex ecological and social processes, and a range of spatiotemporal scales can interfere with their results (Pascual et al., 2010). This study is based on this relevant gap to understand PES project evaluation models better, answering the research question: What is the impact of payment for environmental services programs? Part two of the article will describe some theoretical concepts, such as the theoretical framework. After that, the methodology will be presented in part three to answer this research question. The results obtained in the data collection and their discussions will be described in part four. The conclusions obtained are described in the part five of this article.

THEORETICAL FRAMEWORK

Payment for Environmental Services

The pioneering spirit of PES is credited to the United States, which implemented the Conservation Reserve Program in 1985, which provided economic incentives for soil conservation practices on rural properties. New York City is the greatest example of this PSA program, as in 1997 this city chose to acquire and recover areas of the Catskill Basin to conserve the water supply source, instead of investing in a treatment plant, to serve to the standards of the Safe Drinking Water Act of 1986 (Pereira & Alves Sobrinho, 2017).

In Latin America, the first formal PES programs (although they did not use such terminology) were initiated in the mid-1990s in the Cauca River Valley, Colombia. However, only after Costa Rica instituted the first federal PES program in the world, the Programa de Pagos por Servicios Ambientales (PPSE), in 1997, this type of action began to develop (Hanley, 2014; Martin-Ortega et al., 2013).

Mexico has also played an important role in PES schemes. The federal government, through the National Forestry Commission, instituted the Hydrological Environmental Services Program in 2003 and the Payments for Carbon, Biodiversity and Agroforestry Services Program in 2004. These two programs evolved and, since 2006, have been merged into the National PES Program.

In short, PES initiatives are recurrent around the world. According to Pereira and Alves Sobrinho (2017), there are records of influential programs that occurred in Ecuador, Peru, China, Japan, South Africa, Germany, and France.

Therefore, the basic idea of PSA is to pay those who, directly or indirectly, preserve the environment (Costedoat et al., 2015; Le Velly & Dutilly, 2016; Ruggiero et al., 2019). By definition, PESs are mechanisms that reward those who protect nature. It is a way of 'pricing' ecosystem goods and services and stimulating conservation, assigning them value and constituting a market for the exchange of carbon credits, conservation of water resources, creation of ecological taxes, sustainable exploitation of forests, and sustainable use of biodiversity and ecotourism (Engel, 2016; Jack & Jayachandran, 2019).

Thus, environmental services are those silently provided by nature related to the carbon cycle, the hydrological cycle, scenic beauty, soil conservation, and biodiversity, among others. Therefore, PES ensures better preservation of genetic heritage and traditional knowledge, as well as developing actions to regulate the climate and reduce deforestation, especially in rural areas. Thus, PES contributes to greater incentives for the development of sustainable agriculture (Araújo, 2019; Tacconi, 2012).

The PSE remunerates rural producers for environmental services that benefit society. The beneficiaries of these environmental actions, that is, the whole of society, will be the payers of these remunerations. Therefore, the logic behind the PSA is that environmental conservation must be more profitable than its destruction, and therefore the gains obtained by the environmental service provider must be greater than those that would potentially be obtained in other economic activities that could harm the environment (Tacconi, 2012).

According to Ezzine-de-Blas et al. (2016), payments can be made in several ways: (a) directly (monetary or not); (b) by providing social improvements to rural and urban communities; (c) through compensation linked to a certificate of reduction of emissions from deforestation and degradation; (d) by lending through an environmental reserve quota established by the Forest Code; and (e) through green bonds.

There are several types of PESs: (a) for the preservation of native vegetation; (b) for restoring degraded areas; (c) for improving water quality; (d) for carbon sequestration; and (e) for maintaining biodiversity (Hanley, 2014). Among the various objectives of PES, the most common include: (a) maintenance, recovery, or improvement of vegetation cover in areas considered a priority for preservation; (b) combating habitat fragmentation; (c) the formation of biodiversity corridors; and (d) conservation of water resources (Engel, 2016; Le Velly & Dutilly, 2016).

According to the literature, there is a great diversity of PES programs, in addition to the issue of environmental protection (Game et al., 2018; Tengberg & Valencia, 2018; Wiik, 2020). This approach may be useful for irrigation systems (Lankford et al., 2016), ecotourism (Eshoo et al., 2018), poverty alleviation (Hajjar et al., 2021), and social impacts (Game et al., 2018; Larson et al., 2019), among others.

Brazil has successful examples of PES, which began in the 1990s. The Program for the Socioenvironmental Development of Rural Family Production and the Bolsa Floresta were created in 2003 and 2007, respectively, as pioneer programs of PES and of greater relevance in terms of the use of PES schemes in the Amazon, connected to environmental services linked to carbon, water, soil quality, and biodiversity. However, the Water Producer Program stood out at the federal level. The principle of this program is the concept of a protector-receiver and aims to complement the user-pays and/or polluter-pays policies for the conservation of water resources (Ferreira et al., 2021). In the following section, we present some evaluation models of this type of program to measure their effectiveness.

Program Evaluation

Evaluation is a process that consists of making value judgments about the activities and results of a program, project, policy, or strategy (Kleiman et al., 2016). In turn, the evaluation of the impact of a program necessarily involves two elements: (a) building a detailed and accurate description of the performance of a program and (b) comparison with a criterion or a pre-established standard to judge the performance (Cotta, 2014; Saccol et al., 2004).

There is a wide range of evaluation methods that can be used. For example, program evaluation is an evaluation category that has at least five subcategories of evaluation types: (a) needs assessment; (b) theoretical evaluation; (c) processes; (d) impact; and (e) efficiency (Kleiman et al., 2016).

A needs assessment comprises a systematic study that identifies its nature, scope, and causes. This type of evaluation defines and describes the target population to be served and determines the intervention necessary to address the need (Costa & Castanhar, 2003).

Theoretical evaluation analyzes the theory behind the program, that is, it verifies whether it is viable and feasible and if it meets the needs of the target population. Specifically, the theoretical evaluation describes the theory and, therefore, gives rise to the nomenclature of the so-called theory of change (TC), as well as determining the quality of the project through a literature review, a panel of experts, and interviews (Cotta, 2014).

Process evaluation, in turn, is known as 'from theory to practice.' While TC says how the program should work, process evaluation studies Theoretical evaluation analyzes the theory behind the program, that is, it verifies whether it is viable and feasible and if it meets the needs of the target population. Specifically, the theoretical evaluation describes the theory and, therefore, gives rise to the nomenclature of the so-called theory of change (TC), as well as determining the quality of the project through a literature review, a panel of experts, and interviews what happens in practice and, therefore, evaluates the implementation of a program. Process evaluation describes the evidence obtained, measuring progress toward objectives, during program implementation (Costa & Castanhar, 2003).

Impact evaluation aims to identify the changes generated by the program, that is, this evaluation subcategory measures the progress caused by this program toward the objectives (Sills et al., 2006). It is timely and limited in time and provides causal evidence. Furthermore, it is designed before implementation, with the results after the program is implemented (Finkler & Dellaglio, 2013). The impact assessment is measured by the difference between the beneficiaries' results when participating in the program and the result that these same beneficiaries would obtain in the counterfactual situation, that is, in the hypothetical case of not having participated in the program (Costa & Castanhar, 2003). This measurement makes it possible to show the effective result of the impact that the studied program achieved.

Usually, the impact is evaluated for three main reasons: (a) to improve the program, that is, to generate information focused on the design or reformulation of the program, with the purpose of improving its performance and its results (finding concrete solutions and implementing them in the short term, in addition to understanding the relative importance of the program components and processes); (b) to make public spending more efficient, by issuing a judgment on the efficient use of resources (useful for making decisions regarding the allocation of resources and the continuity of the program, as it is of interest to high-level decision-makers — e.g., governors, mayors, legislators); and (c) to generate knowledge about public policies, that is, generate public goods, contributing to knowledge in social and economic sciences (produces knowledge about the mechanisms and effects of an intervention, as well as serving as a base for innovations and for new approaches, with the potential for replication and for gains of scale) (Costa & Castanhar, 2003). The impact is evaluated when there are causal questions unanswered, when there is uncertainty about the best intervention strategy to tackle a problem when a pilot program is being implemented, when it is planned to scale up a program, when a program is being implemented gradually, or when the program incorporates new services or new beneficiaries (Finkler & Dellaglio, 2013).

The impact assessment methodologies indicated in the literature help managers and investors in decision-making, as they provide the necessary information to improve the planning and management process of their programs. In addition, stakeholders need knowledge about impact evaluation methodologies so that they can measure the impacts of social programs (Rodrigues et al., 2021).

Finally, the efficiency evaluation is a cost-benefit analysis because it compares the benefits (results) of the program with its costs (resources used). Such evaluation involves monetizing costs and benefits and is usually performed ex-ante. In the cost-effectiveness analysis, the efficiency assessment compares the change in the main impact variable with the program costs, thus generating the relative impact of the different interventions. In this case, it is generally carried out ex-post (Cotta, 2014).

Therefore, it is noted that evaluation methodologies allow for evaluating the best use of resources in the search for the best possible result, resulting in continuous improvements in strategies, programs, and public policies (Cotta, 2014). Specifically, in projects that involve PES schemes, the evaluation seeks to understand, in addition to the issue of project transparency (Tacconi, 2012), an expansion of the results of sustainable development (Martin-Ortega et al., 2014). The next section focuses on the theory of change and its relationship to payments for environmental services.

Theory of Change (TC)

It was observed that the theoretical evaluation originated with the theory of change. The TC is a broad and illustrated description of how change is expected to occur in a particular context. Therefore, it is a way to become aware of how far you are going (results) and how you are going to get there (processes), as it details all the implicit changes that must occur between the activities of a program and its long-term objectives (E. P. Santos et al., 2022).

This theory aims at the communication and description of the intervention, the design of the intervention, and strategic planning, monitoring, and evaluation. TC gives rise to the so-called 'logical framework,' a tool that shows how a program's activities are related to its results, objectives, and impacts (Sugahara & Rodrigues, 2019). Thus, the TC can have different forms; it consists of a dynamic map of the program, which shows the cause-and-effect relationship between the elements and the results of an intervention, and it is not only a descriptive but also an explanatory instrument whose results have contextual influence (Escola Nacional de Adminstração Pública [ENAP], 2022).

The theory of change is important, as it helps to design impact evaluation by allowing the identification of evaluation questions, usually related to the assumptions identified by the TC, and by helping define what data to collect and what variables to measure — more specifically, impact evaluation. Therefore, TC defines the most generalizable knowledge and mechanisms to replicate programs in different contexts, by understanding why a program generates certain results (E. P. Santos et al., 2022).

Thus, the theory of change tool makes it possible to define the scope of action of projects and monitor the impact of interventions for later application of an impact evaluation methodology (Sugahara & Rodrigues, 2019). In this context, organizations can rely on TC, a tool for impact evaluation, which describes how a program generates specific long-term results through a logical sequence of intermediate results (Sugahara & Rodrigues, 2019).

Regarding TC and PES programs, the literature widely indicates that TC serves as a basis for the implementation of sustainability-oriented practices. Basically, in all the studies that address TC, there are assumptions that, if met, can help in the process of change and the increase of environmental conservation, the alleviation of poverty, and the improvement of quality of life and human well-being (Lankford et al., 2016). In addition, TC is also considered a means of evaluating the impact of policies to highlight the essential elements of the evaluation process (Sugahara & Rodrigues, 2019; Wegner, 2016). The next part of this article will present the methodology of this scientific study, i.e., how this evaluation process will be performed.

METHODOLOGY

The present study has an explanatory objective, an empirical nature, and a quantitative approach (Gil, 2010). Brazil has several PES initiatives, among which some stand out in the Brazilian Atlantic Forest, due to their importance as seen below.

According to the Ministério da Ciência, Tecnologia e Inovação (MCTI, 2022), the Atlantic Forest covers approximately 15% of the Brazilian territory and is present in 17 states. It is noted that 72% of Brazilians live in this biome. Furthermore, this biome represents 70% of the national gross domestic product (GDP). It is noted that essential services such as water supply, climate regulation, agriculture, fishing, electricity, and tourism also depend on this biome. Due to its climatic characteristics, the Atlantic Forest presents a diverse set of forest ecosystems with very different floristic structures and compositions (E. P. Santos et al., 2022; J. S. Santos et al., 2018).

However, today only 12.4% of the original forest still remains intact; therefore, the Atlantic Forest is one of the most threatened tropical forests in the world, and the Brazilian biome has suffered most from the country's economic cycles since it is home to most metropolitan regions and it is home to major industrial, oil, and port centers in Brazil. However, even with its area reduction over time, the Atlantic Forest is among the five most important sets of ecosystems for preserving the planet's biodiversity. This is because the biome contributes significantly to the reduction of carbon dioxide (CO_2) in the atmosphere and is also a source of food and water for the population (Morellato & Haddad, 2000).

Thus, the PES initiatives developed in the Atlantic Forest focus on rural landowners who adopt actions to preserve the native forest of this biome, recover degraded areas, and implement sustainable production practices to increase carbon stocks, increase the resilience of ecosystems, and promote the protection of the habitat necessary for the preservation of biodiversity through the reconnection of forest fragments (Fundação de Empreendimentos Científicos e Tecnológicos [FINATEC], 2022; MCTI, 2022; Yablonovitch & Deckman, 2023).

Secondary data (geospatial data) were collected to analyze the impacts of these PSA programs in the Atlantic Forest. This is because, with recent technological advances in geospatial data acquisition, processing, cloud-based dissemination, and analysis infrastructure, there is an increasing number of studies that use geospatial data in research related to land use, including in agricultural areas (Bragança et al., 2022; Formigoni et al., 2011; Haces-Fernandez, 2022; Hasenack et al., 2015; Lapola et al., 2008; Souza et al., 2020; Uhl & Leyk, 2022).

Furthermore, according to Formigoni et al. (2011), monitoring vegetation cover through remote sensing and geoprocessing products and techniques is based on the need to analyze plant resources, contributing to monitoring over time and obtaining information such as the distribution of types of vegetation, phenology, canopy structure, stress conditions, and changes in land use. Thus, some studies have shown that the use of sensing and geoprocessing as geospatial models can guide the geographical prioritization of interventions (Roberts et al., 2022), based on the mapping, monitoring, and analysis of changes in land use and cover with greater frequency, greater detail, and better precisi (Rosa, 2016).

One of the tools for making geospatial data available is the MapBiomas project, an initiative of the climate observatory, produced by a collaborative network of cocreators formed by nongovernmental organizations, universities, and technology companies organized by biomes and transversal themes, which seeks conservation and sustainable management of natural resources as a way of combating climate change (Projeto MapBiomas, 2023).

Therefore, these secondary data were collected from MapBiomas, which provides geospatial data through an open platform that processes remote sensing information in partnership with the Google Earth Engine.

More precisely, using the MapBiomas platform, through the interpolation of the Rural Environmental Registry (RER) number provided by the National Rural Environmental Registry System, the polygons of properties located in the study region were collected.

Data from the rural areas participating in the PSE program were acquired on the program's digital platform (MCTI, 2022). Note that the program serves the states of São Paulo, Minas Gerais, and Rio de Janeiro, together with the respective state governments, in addition to the federal government and international development banks. However, it was decided to study only the state of São Paulo because the three typologies of PSE in this program are only present in this state (PSE-Protection; PSE-Usage; and PSE-Value), further described below.

Thus, the study considered all rural producers registered with the RER who were located in the Atlantic Forest biome, in the state of São Paulo, and located in municipalities where there was at least one producer participating in the program. With the complete list of existing rural producers, those participating in the PES were separated from those who did not participate.

For each rural producer, in addition to information from the RER and the georeferenced polygon of each property, the values received by the PSEs were collected in the period between 2018 and 2021. In addition, land occupation for each producer was observed in 2016 and 2021. Table 1 presents the list of cataloged municipalities and the number of farmers participating and not participating in the PSA program.

Table 1. Number of properties selected for the study.

Municipalities — SP	Totals (gross)		With methodological pairing (randomized)	
	Control	Treatment	Control	Treatment
Areias	38	19	19	19
Bananal	74	70	70	70
Cachoeira Paulista	100	7	7	7
Cunha	840	93	93	93
Guaratinguetá	297	18	18	18
Itariri	220	69	69	69
Lagoinha	185	20	20	20
Lorena	112	5	5	5
Miracatu	280	5	5	5
Natividade da Serra	138	137	137	137
Paraibuna	283	44	44	44
Pedro de Toledo	243	50	50	50
Peruíbe	166	20	20	20
Redenção da Serra	105	37	37	37
São José dos Campos	611	88	88	88
São Luiz do Paraitinga	243	107	107	107
Silveiras	115	72	72	72
Taubaté	314	16	16	16
Total	4364	877	877	877

Note. Source: Research data.

In total, 246,947 image fragments were collected, with information on soil use and area, referring to 5,241 rural producers in the study environment, 4,364 from properties not involved in the PES program, and 877 from participating properties. To give the same weight to the verification of land use transition data, it was decided to select, in a random manner, the same number of producers participating in the program in each municipality (treatment producers) and non-participants producers in the same municipality (control producers).

After that, we performed a methodological matching treatment, which resulted in 877 control properties and 877 treatment properties. The existing selection bias occurred at the entrance of rural producers' property through public notices of PES. These are arbitrary choices, by each producer, to adhere or not to PES projects. The controls may or may not have been aware of the program.

Data were analyzed using multivariate statistics such as non-parametric statistics of comparisons between groups and multiple linear regression (Fox & Weisberg, 2020; Hair et al., 2009). These analyses and inferences were performed using Jamovi software. Figure 1 shows a schematic of the adopted method.

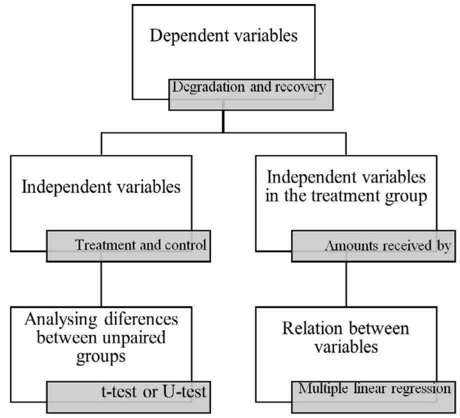

Figure 1. Schematic drawing of the adopted method.
Source: Developed by the authors.

With the scope of the structured study sample, as well as the design of the method, the indicators that correspond to the object of this study were defined: degraded areas and recovered areas (in hectares) from 2016 to 2021. These two indicators are the dependent quantitative variables, as shown in Figure 1, where the analysis groups are the control and treatment properties.

In addition to the comparative analysis, we evaluated the influence of the three types of PSEs that producers received as independent variables of degradation and recovery. There are three types of PESs in the program: (1) the PES-Protection is aimed exclusively at the protection of consolidated areas considered 'protected,' either through the enrichment of the biome or the fencing of protected areas, among other aspects; (2) PES-Use is based on payment for improving land use, that is, implementing species diversity in pasture or encouraging agroecological practices, among others; and (3) finally, there is a payment for the agricultural production value chain, in which there is a stimulus in the differentiation and improvement of the quality of the rural production of the participating producers, called PSE-Value.

Two methods of statistical inferences were made: (1) a comparison of the two groups (control and treatment) regarding their property sizes; and (2) a multiple linear regression using these two groups as independent quantitative variables for the dependent variables of the calculated area of degradation and recovery. Because they are independent groups and not statistically paired, the t-test for two independent samples could be used (in the case of normally distributed data), or the Mann-Whitney U test could be used (if the data were not normally distributed). In the other inference, we used multiple linear regression to evaluate the influence of the predictor variables of payments received by the type of PES on the dependent variables of degradation and recovery area. The dependent variables were collected as images (raster images), and only the data from polygons inserted within the rural properties selected in the scope of the study were treated. Figure 2 shows the data collected.

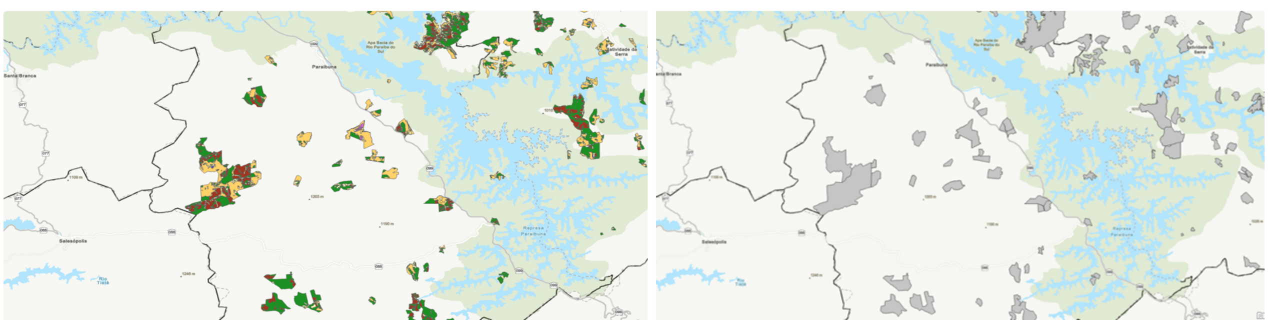

Figure 2. Example of an area with land use polygons (first image), followed by a cutout of the same region with the areas of the properties of interest (second image).
Source: Survey data.

As exemplified in Figure 2, the images of the land use indicators are aligned with the polygons of the properties of interest. When systematizing all the polygons of interest, the data were transferred to a table, which presents information such as the size of each land use classification, size in hectares, and which property is included in such information. The system informs that the minimum size of clear information for analysis is a pixel, measuring 30 meters by 30 meters (Projeto MapBiomas, 2023). Therefore, polygons with degradation or recovery information smaller than 0.09 hectares were not considered in the analysis. Land use information was classified by the system as shown in Table 2.

Table 2. Land use classification of the system.

Classification
Aquaculture
Coffee
Forest Formation
Forest Plantation
Grassland
Herbaceous Sandbank Vegetation
Mining
Mosaic of Agriculture and Pasture
Mosaic of Crops
Other Non-Vegetated Area
Other Perennial Crops
Pasture
River, Lake, and Ocean
Rocky outcrop
Salt flat
Savanna Formation
Soybeans
Sugar Cane
Urban Infrastructure
Wetland
Wooded Sandbank Vegetation

Note. Source: Based on Souza et al. (2020).

With the land use classifications indicated in each polygon in 2016 and 2021, it was possible to group the land use transition in the period, i.e., whether the land use changed from one classification to another or if it remained. In this context, a transition grouping was created for the types of land use change that occurred in each processed polygon. As the search for a clustering method in the literature was unsuccessful, a first cluster was performed with field experts from the program. Next, the grouping categories were validated with the program's technical team since its implementation. Through a semi-structured interview with this team, three groups of land use transitions were considered:

(1) No influence: when there is no change in land use in the period or the change does not contribute to a decrease or increase in the biological diversity or quality of the environment (systems with increased soil organic matter, formation of watersheds, among other ecosystem agents).

(2) Recovery: when there is a contribution to improving the environmental quality of the transition that occurred. For example, a pasture that was converted to a coffee area was considered an environmental gain, just as a coffee area changed to a forest area.

(3) Degradation: when there is a contribution to environmental deterioration in the study area, i.e., an area of forest cleared for agriculture or even an area of coffee plantation for pasture, degradation was considered for the study.

Table 3. Categorization of transitions adopted in the study.

Classification 2016	Classification 2021	Transition
Aquaculture	Aquaculture	No influence
Aquaculture	Mosaic of Agriculture and Pasture	Degradation
Aquaculture	River, Lake and Ocean	No influence
Coffee	Coffee	No influence
Coffee	Forest Formation	Recovery
Coffee	Mosaic of Agriculture and Pasture	No influence
Coffee	Pasture	Degradation
Coffee	Mosaic of Crops	No influence
Forest Formation	Coffee	Degradation
Forest Formation	Forest Formation	No influence
Forest Formation	Mosaic of Agriculture and Pasture	Degradation
Forest Formation	Mosaic of Crops	Degradation
Forest Formation	Pasture	Degradation
Forest Formation	River, Lake and Ocean	Degradation
Forest Formation	Rocky outcrop	Degradation
Forest Formation	Wetland	No influence
Forest Formation	Forest Plantation	Degradation
Forest Formation	Savanna Formation	No influence

(continues)

Table 3. Categorization of transitions adopted in the study. (continued)

Classification 2016	Classification 2021	Transition
Forest Formation	Grassland	Degradation
Forest Plantation	Forest Formation	Recovery
Forest Plantation	Mosaic of Agriculture and Pasture	Degradation
Forest Plantation	Pasture	Degradation
Forest Plantation	Forest Plantation	No influence
Forest Plantation	Grassland	Degradation
Grassland	Grassland	No influence
Grassland	Pasture	No influence
Grassland	Forest Formation	Recovery
Grassland	Mosaic of Agriculture and Pasture	No influence
Grassland	Mosaic of Crops	No influence
Grassland	Forest Plantation	Recovery
Grassland	Grassland	No influence
Grassland	Mosaic of Agriculture and Pasture	No influence
Grassland	Herbaceous Sandbank Vegetation	No influence
Herbaceous Sandbank Vegetation	Mosaic of Agriculture and Pasture	Degradation
Herbaceous Sandbank Vegetation	Wetland	No influence
Mining	Mining	No influence
Mosaic of Agriculture and Pasture	Forest Formation	Recovery
Mosaic of Agriculture and Pasture	Coffee	Degradation
Mosaic of Agriculture and Pasture	Mosaic of Agriculture and Pasture	No influence
Mosaic of Agriculture and Pasture	Mosaic of Crops	Recovery
Mosaic of Agriculture and Pasture	Other Non-Vegetated Area	No influence
Mosaic of Agriculture and Pasture	Other Perennial Crops	Recovery
Mosaic of Agriculture and Pasture	Pasture	Degradation
Mosaic of Agriculture and Pasture	River, Lake and Ocean	No influence
Mosaic of Agriculture and Pasture	Rocky outcrop	Recovery
Mosaic of Agriculture and Pasture	Soy Beans	Degradation
Mosaic of Agriculture and Pasture	Urban Infrastructure	No influence
Mosaic of Agriculture and Pasture	Wetland	Recovery
Mosaic of Agriculture and Pasture	Wooded Sandbank Vegetation	Recovery
Mosaic of Agriculture and Pasture	Forest Plantation	Recovery
Mosaic of Agriculture and Pasture	Savanna Formation	No influence
Mosaic of Agriculture and Pasture	Grassland	No influence
Mosaic of Crops	Forest Formation	Recovery
Mosaic of Crops	Mosaic of Agriculture and Pasture	Recovery
Mosaic of Crops	Mosaic of Crops	No influence
Mosaic of Crops	Other Non-Vegetated Area	No influence
Mosaic of Crops	Pasture	Degradation
Mosaic of Crops	River, Lake and Ocean	No influence
Mosaic of Crops	Rocky outcrop	No influence
Mosaic of Crops	Soy Beans	Degradation
Mosaic of Crops	Sugar Cane	Degradation
Mosaic of Crops	Urban Infrastructure	No influence
Mosaic of Crops	Wetland	Recovery
Mosaic of Crops	Wooded Sandbank Vegetation	Recovery
Mosaic of Crops	Forest Plantation	Recovery
Mosaic of Crops	Coffee	No influence
Other Non-Vegetated Area	Mosaic of Agriculture and Pasture	Recovery
Other Non-Vegetated Area	Mosaic of Crops	Recovery
Other Non-Vegetated Area	Other Non-Vegetated Area	No influence

(continues)

Table 3. Categorization of transitions adopted in the study. (continued)

Classification 2016	Classification 2021	Transition
Other Non-Vegetated Area	River, Lake and Ocean	No influence
Other Non-Vegetated Area	Urban Infrastructure	No influence
Other Non-Vegetated Area	Pasture	Recovery
Other Non-Vegetated Area	Rocky outcrop	No influence
Other Perennial Crops	Other Perennial Crops	No influence
Pasture	Forest Formation	Recovery
Pasture	Coffee	Recovery
Pasture	Mosaic of Agriculture and Pasture	Recovery
Pasture	Mosaic of Crops	Recovery
Pasture	Other Non-Vegetated Area	Recovery
Pasture	Other Perennial Crops	Recovery
Pasture	Pasture	No influence
Pasture	River, Lake and Ocean	No influence
Pasture	Rocky outcrop	No influence
Pasture	Soy Beans	No influence
Pasture	Sugar Cane	Recovery
Pasture	Urban Infrastructure	No influence
Pasture	Forest Plantation	Recovery
Pasture	Grassland	No influence
River, Lake and Ocean	Forest Formation	Recovery
River, Lake and Ocean	Mosaic of Agriculture and Pasture	Degradation
River, Lake and Ocean	Mosaic of Crops	Degradation
River, Lake and Ocean	Other Non-Vegetated Area	Degradation
River, Lake and Ocean	Pasture	Degradation
River, Lake and Ocean	River, Lake and Ocean	No influence
River, Lake and Ocean	Rocky outcrop	Degradation
River, Lake and Ocean	Forest Plantation	No influence
Rocky outcrop	Forest Formation	Recovery
Rocky outcrop	Mosaic of Agriculture and Pasture	Degradation
Rocky outcrop	Pasture	Degradation
Rocky outcrop	Rocky outcrop	No influence
Rocky outcrop	Forest Plantation	No influence
Salt flat	Salt flat	No influence
Savanna Formation	Savanna Formation	No influence
Savanna Formation	Forest Formation	Recovery
Savanna Formation	Mosaic of Agriculture and Pasture	No influence
Savanna Formation	Rocky outcrop	Degradation
Soy Beans	Mosaic of Agriculture and Pasture	Recovery
Soy Beans	Mosaic of Crops	Recovery
Soy Beans	Other Perennial Crops	Recovery
Soy Beans	Pasture	No influence
Soy Beans	Soy Beans	No influence
Sugar Cane	Mosaic of Crops	Recovery
Sugar Cane	Pasture	No influence
Sugar Cane	Sugar Cane	No influence
Urban Infrastructure	Urban Infrastructure	No influence
Wetland	Forest Formation	Recovery
Wetland	Mosaic of Agriculture and Pasture	Degradation
Wetland	Mosaic of Crops	Degradation
Wetland	Wetland	No influence
Wetland	Wooded Sandbank Vegetation	No influence

(continues)

Table 3. Categorization of transitions adopted in the study. (continued)

Classification 2016	Classification 2021	Transition
Wooded Sandbank Vegetation	Mosaic of Agriculture and Pasture	Degradation
Wooded Sandbank Vegetation	Mosaic of Crops	Degradation
Wooded Sandbank Vegetation	Wetland	No influence
Wooded Sandbank Vegetation	Wooded Sandbank Vegetation	No influence
Other Non-Vegetated Area	Urban Infrastructure	No influence
Other Non-Vegetated Area	Pasture	Recovery
Other Non-Vegetated Area	Rocky outcrop	No influence
Other Perennial Crops	Other Perennial Crops	No influence
Pasture	Forest Formation	Recovery
Pasture	Coffee	Recovery
Pasture	Mosaic of Agriculture and Pasture	Recovery
Pasture	Mosaic of Crops	Recovery

Note. Source: Basead on Souza et al. (2020).

Statistical analyses were performed based on the information on the transition groups (Table 3) as well as the indication of each property (including values received by the type of PES program). Next, the results are presented, and their discussion is divided into three parts, which are presented below.

RESULTS AND DISCUSSION

Evaluation between groups

Table 4 shows the descriptive statistics of the analysis. Initially, there was a sample of 877 areas of interest for each treatment. By disregarding properties in which there was no degradation or recovery, the adjusted sample was subjected to inference.

There is a median of 1.306 hectares of treated property and 1.023 hectares of control property in the category of transition to degradation. During the transition to recovery, there were 1.346 hectares in the transition treatment group and 0.936 in the control group. The median was used to measure the central tendency because the assumption of normality of the data was not met in all cases, as observed in the Shapiro-Wilk test (< 0.001), which rejects the null hypothesis of normality of these data at the 1% significance level. Therefore, the comparisons between the two groups were performed using the nonparametric Mann-Whitney U test, as shown in Table 5.

Table 4. Descriptive statistics of the relationships between groups.

							Shapiro-Wilk	
Transition	Treatment	No.	Median	Standard deviation	Minimum	Maximum	W	p
Degradation	Treatment	346	1.306	5.96	0.0937	59.4	0.443	< 0.001
	Control	318	1.023	6.45	0.0922	74.6	0.355	< 0.001
Recovery	Treatment	591	1.346	4.19	0.0941	45.2	0.522	< 0.001
	Control	495	0.936	3.22	0.0908	22.3	0.614	< 0.001

Note. Source: Research data.

Table 5. Mann-Whitney U test for independent samples.

Transition	Test	Statistics	p
Degradation	U of Mann-Whitney	50571	0.072
Recovery	U of Mann-Whitney	126235	< 0.001

Note. Source: Research data.

The results of this test show that at the 1% significance level there is a difference in the central tendency (median) of the recovery indicator between the treatment and control groups. Therefore, there is a significant difference between the recovery areas existing in the properties participating in the programs and those that do not participate in the programs. In degraded areas, it is noted that there was no significant difference at the same level adopted by the study, that is, there was no significant difference between the PSA programs for indicators of degradation of rural properties at the 5% level.

Evaluation of the relationships between the variables

After these analyses, the treatment properties were separated from the recovery areas and the three types of payments for environmental services presented were inferred (Table 6).

Table 6. Descriptive statistics for areas under recovery.

Transition (Recovery)	No.	Mean	Standard deviation	Minimum	Maximum	Shapiro-Wilk w	Shapiro-Wilk p
Recovery	543	2.67	4.32	0.100	45.2	0.518	< 0.001
Ln (recovery in m^2)	543	9.51	1.15	6.908	13.0	0.995	0.059

Note. Source: Research data.

Overall, 543 properties with recovery areas received some PES amount. There was an average of 2.67 hectares in recovery during the study period. Due to non-compliance with the assumption of normality of the original recovery values (given by the rejection at the 1% level of the null hypothesis of the Shapiro-Wilk test), two transformations were performed on these data: (a) the value of hectares was transformed into square meters and (b) the Naperian logarithm of this value in square meters was taken. These transformations aimed to facilitate the interpretation of the results and obtain a normal distribution of these data, a requirement to use multiple linear regression, which is presented in Table 7.

As shown in Table 7, the transformed data demonstrate normality, heteroscedasticity, and multicollinearity. Thus, one can proceed with the linear regression (Tables 8 and 9).

Table 7. Verification of assumptions for statistical inference.

Normality test	Statistics	p
Shapiro-Wilk	0.997	0.428
Kolmogorov-Smirnov	0.0231	0.933
Anderson-Darling	0.411	0.341
Heteroscedasticity test	**Statistics**	**p**
Breusch-Pagan	1.39	0.708
Goldfeld-Quandt	1.07	0.286
Harrison-McCabe	0.483	0.321
Collinearity statistics	**FIV**	**Tolerance**
PSE-Protection	1.08	0.926
PSE-Use	1.17	0.851
PSE-Value	1.16	0.864

Note. Source: Research data.

Table 8. Measures of fit of the model.

Global model test						
Model	R	R^2	F	gl1	gl2	p
1	0.406	0.165	35.4	3	539	< 0.001

Note. Source: Research data.

Table 9. Model coefficients — Ln (recovery — in m²)

Predictor	Estimates	Standard error	t	p
Intercept	9.0227	0.06867	131.3907	< 0.001
PES-Protection - in thousand R$	0.0202	0.00215	9.3946	<0.001
PES-Use - in thousand R$	0.0230	0.00393	5.8625	< 0.001
PSE-Value - in thousand R$	-2.50e–4	0.00337	-0.0740	0.941

Note. Source: Research data.

Table 8 shows an R2 value of 0.165, that is, the explanatory power of the model to the variance of this data distribution is 16.5%, following a trend observed in studies in the areas of environmental and ecological research (Low-Décarie et al., 2014). . In Table 9, it is observed that in addition to the intercept, the independent variables PSA-Protection and PSA-Use have a significance level of 1% in the proposed model. The PSE value was not significant in this model, indicating that it does not influence the recovery area. The model equated according to multiple linear regression is presented below:

$$e^{recuperação/10000} = e^{9.0227+\left(\frac{0.0202*PSE-Protection}{1000}\right)+\left(\frac{0.0230*PSE-Use}{1000}\right)+\left(\frac{0*PSE-Value}{1000}\right)}$$

The values of PSE-Protection, PSE-Use, and PSE-Value are in thousands of Brazilian reais to facilitate the presentation of results (about US$ 187.09). In the equation, the conversion to integer values is already performed. The areas under recovery are square meters. The conversion to hectares was implemented. Finally, as the data were normalized by Neperian logarithm, the reversion to the data in original numbers was considered.

Thus, for each value scale of PES-Protection and PES-Use, there are different estimated results for the size of the recovery areas. As an example, a data set is shown considering a suggested value of R$ 100,000.00 (about US$ 18,708.72) on a scale of: (1) 100% for PSA-Protection; (2) 50% for each type of PSA; (3) 100% for PSA-Use; and (4) without investment (Table 10).

Table 10. Results of the amounts invested per average area reclaimed.

Area/R$ 100,000 (US$ 18,708.72)	R$ 100,000 (US$ 18,708.72) PSE-Protection	R$ 50,000 (US$ 9,354.36) PSE-Protection R$ 50,000 (US$ 9,354.36) PSE-Use	R$ 100,000 (US$ 18,708.72) PSE-Use	No investment
Recovery of degraded areas in hectares	6.24 ha	7.19 ha	8.26 ha	0.83 ha

Note. Source: Research data.

For every R$ 100,000.00 (about US$ 18,708.72) invested in paying for environmental services, there is a gain in recovery area between 6.24 and 8.26 hectares, depending on the type of PES to be applied. When there was no investment, the gain in the area recovered for the region was on average 0.83 hectares in the study period. Therefore, the counterfactual of the project was a simulated value of R$ 100,000.00 (about US$ 18,708.72) and the recovered area was between 5.41 and 7.43 hectares over the period.

Evaluation of the types of PSE

The latter approach allows visualization of the various PSE amount scales ranging from R$ 0.00 to R$ 200,000.00 (about US$ 37,417.45), with the same values distributed in the two impact PSEs (PSE-Protection labeled as 'P' and PSE-Use as 'U'). We considered the distribution between 0% and 100% in each of them with an interval of 10% between the scales. Thus, the curves of each distribution scale by type of PSE are visualized in Figure 3.

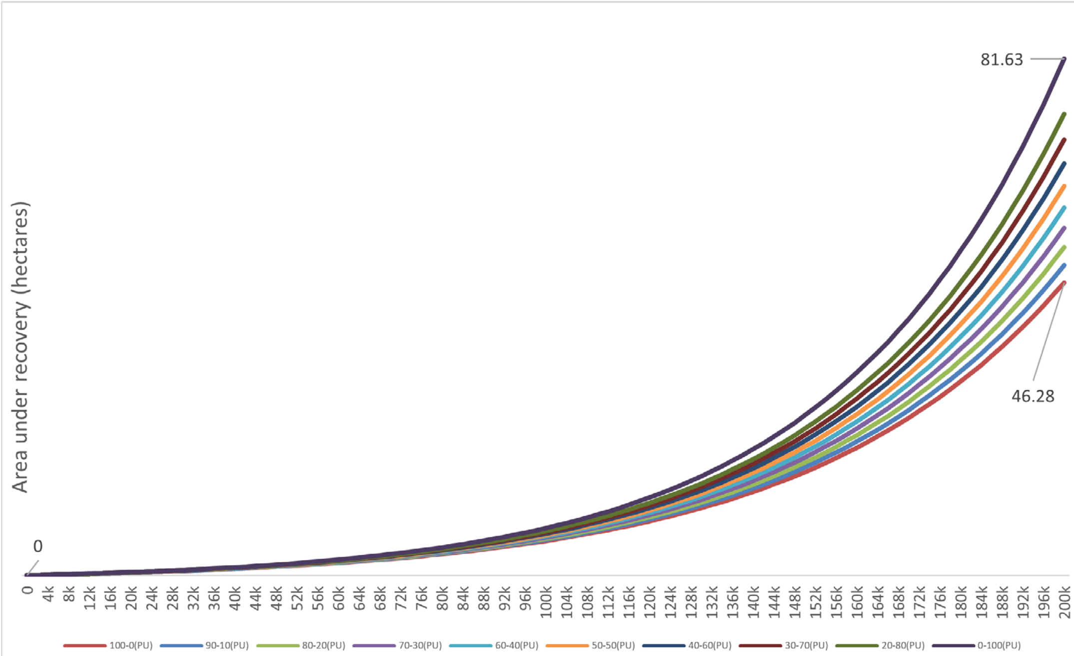

Figure 3. Line graph with simulation of total PSE values with area size for recovery.

Note. Source: Research data.

Figure 3 presents ten distribution scales of the total amounts paid, ranging from 100% for one type of PSE and 0% for the other PSE to 0% for the first type and 100% for the second. The legend of the lines indicates the distribution in 10% intervals, with 'P' indicating PSE-Protection and 'U' indicating PSE-Use. As an example, '100-0(PU)' is 100% PSE-Protection and 0% PSE-Use for the totals observed on the horizontal axis. The vertical axis shows the recovery areas in hectares. Thus, the best line of investment for recovery is the '0-100(PU)' with 81.63 hectares in the simulation. The best investment is to use 100% of the resource in PSA-Use, which would generate a relative cost of R$ 2,392.05 (about US$ 447,52) per hectare for an investment of R$ 200,000 (about US$ 37,417.45). However, this differentiation of PES models only effectively occurs from the investment value of R$ 112,000.00 (about US$ 20,953.77). Below that, the differentiation is minimal and considered negligible.

CONCLUSIONS

Around the world, PES actions have become a very popular tool for the conservation and restoration of ecosystem services, providing economic incentives for environmental conservation. PES schemes have also become a popular strategy complementary to existing conservation strategies such as protected areas.

This study aimed to understand the impact of the PES on several environmental indicators of land use transition grouped into areas with similar aspects of degradation and recovery in the Brazilian Atlantic Forest biome between 2016 and 2021. The secondary data of a PES program adopted in the state of São Paulo were collected between 2018 and 2021 with the values received by producers in three types of PES.

It is noted that there is an increase in the recovery areas of farmers who participate in the program compared to non-participating producers. This confirms that PSA programs allow the expansion of recovered areas in rural communities. However, there was no significant difference in the impact of the program on the size of the degraded areas.

The program does not affect the reduction of land use transition in terms of degradation. A first assumption could be made by understanding that the rural producer would respond only to the object of the PES — in this case, the payment for what he recovers and not what he stops degrading. In addition to suggesting the need for more in-depth studies in this sense, there is a warning to managers of PSA-type programs about the need to incorporate the requirement that in addition to the recovery of areas, tools should be created to inhibit the degradation of others areas, even if the balance is positive.

When analyzing the influence of the type of PES adopted, it is observed that payments that are not directly linked to the recovery of areas do not cause changes in land use. However, when linked to the recovery areas, there are significant changes. The modality of payments for land use had a greater impact than the payment for protection. The aspect of complexity in the environmental actions of rural producers is reinforced because they meet the program requirements: when they are protected, they focus on recovery areas; when in land use, they focus on all areas subject to recovery including cultivation areas, in addition to the preservation areas of the property.

The Atlantic Forest biome is an important source of natural resources for a large part of the Brazilian population. Therefore, this study mainly focused on the following United Nations (UN) Sustainable Development Goals (SDGs): SDG 1, SDG 2, SDG 6, SDG 11, and SDG 15.

Such platforms could serve to not only continuously evaluate and monitor the effects of PES, but also to increase transparency and engagement with the general public and specific stakeholders. We recommend the development of digital platforms that allow the generation of detailed reports on the impact of PES like the Global Reporting Initiative (GRI) in the context of environmental, social, and governance (ESG) practices. Such platforms could serve to not only evaluate and continuously monitor the effects of PES, but also to increase the transparency and engagement of the general public and specific stakeholders. It is imperative to consider that PES not only serves to remedy the damage that has already occurred, but also has significant potential to prevent environmental degradation, especially in sensitive biomes such as the Atlantic Forest.

It is worth mentioning that this study has limitations. First, the collection of environmental indicators was not synchronized with the period of the program. In addition, many actions of the program can be internalized years after its implementation, such as the formation of a forest canopy. Finally, the grouping of land use transition in reclaimed areas relied on expert analysis only, as there are no consolidated theoretical studies for such grouping. There is a gap in the studies that consolidate the categorization method into objective criteria, such as recovery and degradation. However, it should be noted that despite the limitations, the indication of a grouping method is a contribution of this work to the academic community.

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