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A Bioeconomic Approach to Sustainable Forest Management

In the Colombian Amazon

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Keywords: Bioeconomy, Ecosystem services, Forest policy, Optimal control, Social welfare, Tropical forest conservation.

JEL Codes: L73, O13, Q23, Q57, R14

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Abstract

Sustainable Forest Management (SFM) is based on a rational planning process for forest supply and norms and regulations for the protection and sustainability of natural forests. In Colombia, SFM has been identified as a strategy to avoid deforestation and to favor the economy of households living in forests. However, timber harvesting of natural forests is currently carried out as a subsistence activity, generating low income and negative impacts on ecosystems. This study develops a discrete time bioeconomic model for SFM, with an objective function that is based on the economic impact on timber extraction yields of three commercial species, Achapo (*Cedrelinga cateniformis*), Cabuyo (*Eschweilera coriacea*) and Dormidero negro (*Parkia discolor*), located in the Guaviare region (Colombian Amazon). Our results show that the maximum benefits from sustainable forest harvesting of the three species are achieved in a 25-year span, with net benefits per hectare of USD 498.3, for a planning horizon of 50 years. Sustainable forest harvesting was found to be robust with respect to a number of assumptions in the model. These results provide a scientific basis for harvesting authorizations and permits. Policy implications are discussed.

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1. Introduction

Colombian forestry has substantial economic potential, with nearly 25 million hectares deemed suitable for establishing commercial forest plantations (UPRA, 2015), and roughly 60 million hectares covered by natural forests, of which nine million hectares are designated as protected areas (IDEAM, 2022). Despite its economic potential, the sector faces a concerning trade imbalance that has worsened in recent years. This is evident when comparing trade data from the first half of 2021 to data from the same period in 2020, where there was a noticeable increase in imports and a decrease in exports, resulting in a widening trade gap[1] (MADR, 2021). Several factors contribute to the increase in imports, e.g., the superior quality of imported products, more competitive pricing (particularly for wood particle board), stringent domestic regulations on timber production and processing, and instability in the supply of wood (ONFA and Minambiente, 2016). Deficient road infrastructure, limited production capacity, and temporary factors such as decreased demand, are factors that contribute to the decline in exports (Profor, 2018).

According to IDEAM[2] (2013), legal mobilization of wood obtained from natural forests averaged around two million cubic meters per year (m^3/year) during the 2000s, with only approximately 500,000 m^3/year mobilized in 2021[3] (MADR, 2021). This has led to a greater reliance on less eco-friendly alternatives, i.e., plastics and other petroleum-based derivatives, to replace the demand for wood-based products (ONFA, GGGI, and DNP, 2019). Moreover, deforestation continues to escalate, with 171,685 hectares deforested in 2020 and another 170,000 in 2021. 65% of the deforestation is concentrated in regions like Caquetá, Meta, and Guaviare (IDEAM, 2022).

The social dimension of Colombian forests is highlighted by Victorino (2012). According to her study, by 2011 there were 710 indigenous reservations located mainly in the Amazon, and over four million people from black communities residing in the forests of the Pacific, inter-Andean valleys, and the Caribbean coast. There were also a significant

[1] In terms of value in dollars, the wood and wooden furniture sector in Colombia witnessed a significant disparity in trade balance. Comparing the year 2021 to 2020, exports experienced a growth of 40%, while imports saw a more substantial growth of 66.2%. Similarly, comparing 2022 to 2021, exports showed a modest growth of 1.9%, whereas imports exhibited a more substantial growth of 23.8%. These figures indicate a negative trade balance for the wood and wooden furniture sector in both cases.

[2] Institute of Hydrology, Meteorology and Environmental Studies; IDEAM by its acronym in Spanish.

[3] The data relates to products sourced from protective plantations regulated by environmental authorities.

number of peasant communities and settlers[4] living in forested areas, some legally entitled and others residing in vacant areas. These communities rely heavily on the ecosystem services provided by forests as a source of livelihood. However, the absence of a well-organized value chain and the high costs associated with logging and timber use (ONFA and EFI, 2019), lead many to choose cattle rearing and transitory crops as a more profitable way of generating income. The resultant clearance of forests from this land use change is one of the major factors behind biodiversity loss in the country (WWF, 2022).

In recent years, Colombia has adopted a community-based approach to Sustainable Forest Management (SFM) as a strategy to prevent deforestation and improve community well-being. This is reinforced by the implementation of new policies[5] aimed at promoting forest economics. International cooperation provides additional support for the development of SFM projects. As a result, 32,000 hectares of forests are now effectively managed under SFM, and an additional 259,000 hectares are currently under some management initiative. Importantly, areas effectively managed under SFM show significantly lower deforestation rates (Castellanos et al., 2022).

Despite these efforts, the use of timber and non-timber forest products remains a subsistence economic activity, mainly carried out under informal conditions (ONFA and EFI, 2019). Yet, logging and timber use do not require long waiting periods to generate a cash flow and payback periods do not usually exceed that of certain agricultural crops. In the Colombian Amazon, e.g., the Guaviare region, the cultivation of certain crops like rubber can require up to eight years before economic returns are realized. In contrast, timber harvesting provides a more immediate source of income once environmental authorities grant permission to harvest. Timber users can begin selling their products as soon as they are released onto the market. It is also important to mention that obtaining a forest exploitation resolution from the environmental authority can be a time-consuming and resource-intensive process, which poses a challenge for rural communities with limited technical and economic

[4] Settlers are defined as people who are not native to the place but play an important role in the formation of farms in the country's wastelands.

[5] Among these policies, the following stand out: the National Strategy for the Control of Deforestation and Forest Management in year 2017, the Green Growth Policy (CONPES 3934 of 2018), and the National Policy for Deforestation Control and Sustainable Forest Management (CONPES 4021, 2021).

capacity to engage in SFM as an economic alternative. As a result, SFM requires robust institutional and socioeconomic management planning to ensure its viability.

Although the current regulation[6] on forest exploitation is intended to promote the preservation of forest resources, several technical aspects of the regulations do not have a scientific foundation[7], for instance, the ideal harvesting period, minimum diameter for cutting, and maximum volume for extraction based on forest type and species. Further, efficient utilization of forest resources and economic analysis in support of SFM need to consider both the biological limitations of natural forests and the well-being of communities. To address these challenges, discrete time bioeconomic models can be used to incorporate such constraints into the optimization process (Holmes and Sills, 2015).

The aim of this paper is to provide evidence for the use of SFM as a conservation strategy for forests and a source of stable income for communities that rely on forest resources. We develop a discrete time bioeconomic model of forest use that maximizes the economic yield of three commercial forest species: Achapo (*Cedrelinga cateniformis*), Cabuyo (*Eschweilera coriacea*), and Dormidero negro (*Parkia discolor*). Our model was applied to the case of the Guaviare region, located in the Colombian Amazon, due to its significance for post-conflict[8] and its recognition as an area where deforestation presents a pressing challenge. The selected species are widely available in the study area and in the current market for timber products. The optimization process was subject to biological restrictions directly related to the available volume of the species, their growth rates, and the discount rate. These variables impact the volume of timber that can be sustainably harvested, and the length of the cutting cycle required for resource renewal. Our results reveal that

[6] The Ministry of Environment and Sustainable Development (Minambiente, abbreviation in Spanish) oversees the regulation of natural forests while regional environmental authorities act as administrators of these resources, providing regional-level control and surveillance. The norm that regulates forest exploitation is Decree 1791 of 1996, compiled in the sole Decree of the Environmental Sector 1076 of 2015.

[7] There are some exceptions, for instance, the Cativo (*Prioria copaifera*) forests in the Medio Atrato region. These forests were managed by a private company for veneer production.

[8] The four municipalities within the department are part of Development Programs with a Territorial Focus (PDET, by its acronym in Spanish), a strategic initiative implemented by the national government to foster the economic, social, and environmental development of regions severely impacted by the internal armed conflict.

sustainable harvesting of the selected species can yield maximum benefits within an optimal 25-year cutting cycle, resulting in a net benefit of COP 1,999,040 (USD 498.3)[9] per hectare over a 50-year planning horizon. By comparing the outcomes of our bioeconomic model with the current status quo, we identify and discuss significant implications for future policy design.

The remainder of the paper is organized as follows. Section 2 introduces the case study and reviews the relevant literature. Section 3 outlines the modelling approach, presents a literature review, and describes the data collection and analysis procedures. Section 4 summarizes and discusses the obtained results, while Section 5 draws conclusions.

2. Context

2.1 Study area

In the Guaviare region (Figure 1), the utilization and extraction of forest resources have been predominantly restricted to domestic use (Cooagroitilla and ONFA, 2021). Despite not being commonly associated with commercial logging, Guaviare presently experiences one of the highest deforestation rates in Colombia, with 34,527 hectares deforested in 2018 (Figure 2). This accounts for 17% of the total national deforestation that year, which reached 197,159 hectares (IDEAM, 2021). The main factors behind this deforestation trend include illegal land appropriation[10], road expansion, extensive livestock farming, agroindustry, illicit crop cultivation, and mining (FCDS, 2022).

[9] As a reference, one USD is equivalent to 4,012 Colombian pesos (COP). This exchange rate information is based on the conversion rate obtained on July 18, 2023.

[10] Notice that, after the Colombia's 2016 Peace Accord, there has been an increased interest in land appropriation and the expansion of activities by armed groups and other economic actors. Prior to the Accord, the Revolutionary Armed Forces of Colombia (FARC) exercised territorial control by imposing limitations on grazing, burning, and the entry of new economic actors (personal interviews with inhabitants of the region, year 2019).

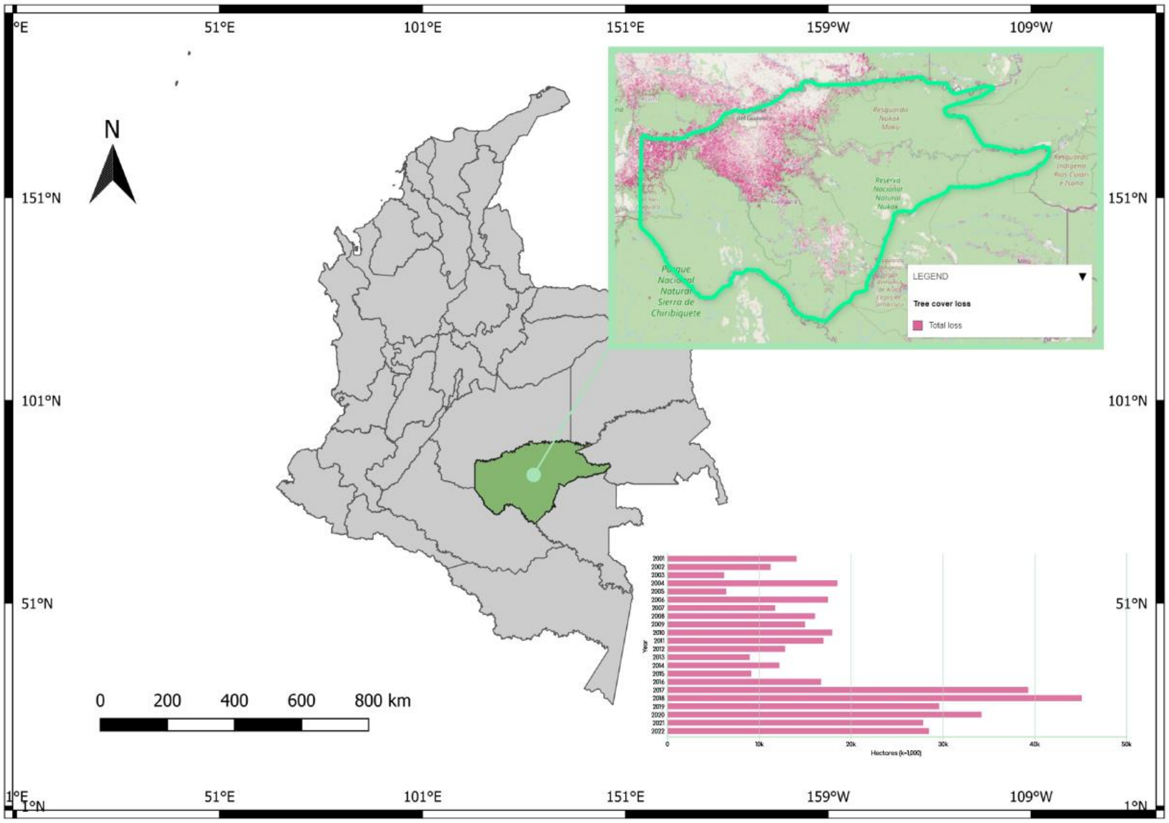

Figure 1. Geographical location and dynamic changes in tree cover loss within the Guaviare region. Source: Own elaboration with data from the Global Forest Watch.

The resources primarily impacted by deforestation are dense tall forests of the Amazon, characterized by tree-type vegetation covering over 84% of the total area, with a canopy height exceeding 15 meters. These forests are typically located in non-flooded regions (SINCHI, 2009). The deforestation of such ecosystems has severe negative environmental consequences, including the loss of habitat for fauna, biodiversity, and other crucial ecosystem services like water regulation. Over time, this can result in water scarcity, avalanches, and floods. Moreover, deforestation carries profound socioeconomic ramifications as it disrupts the livelihoods and survival of communities dependent on forests, often resulting in their displacement (FAO, 2022).

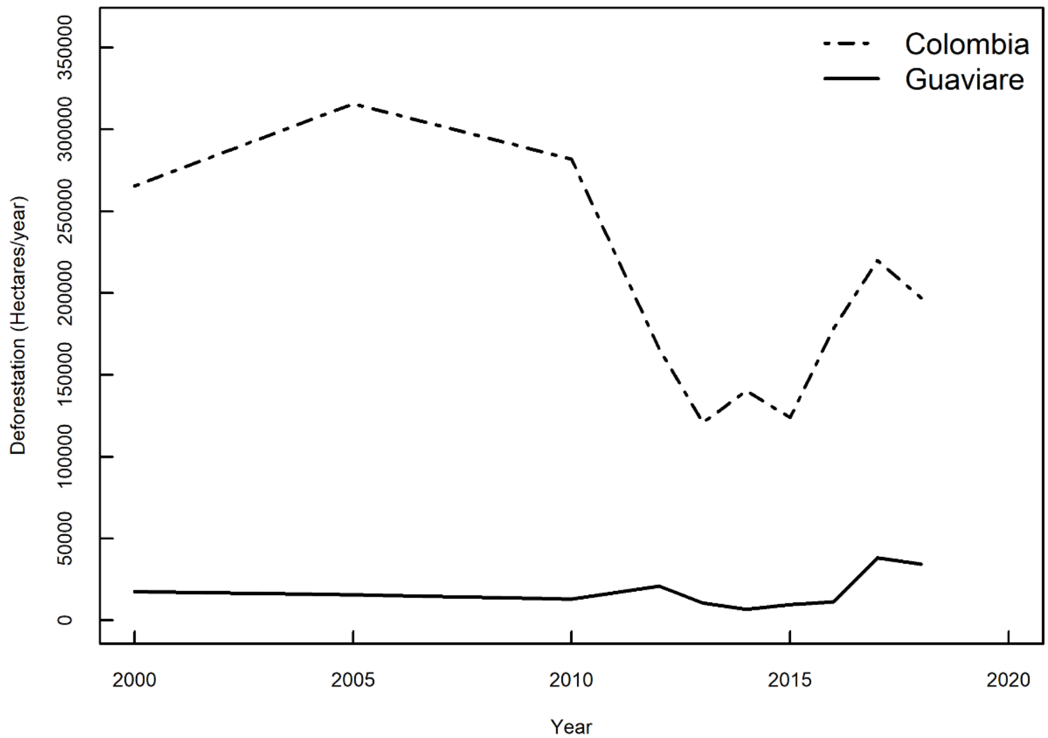

Figure 2. Average annual deforestation in Colombia and Guaviare, 2000 – 2018 period. Source: Own elaboration with data from IDEAM (2022).

In collaboration with international cooperation, the Ministry of Environment supports community-based forestry projects in the region to promote conservation efforts and enhance the well-being of local communities (Castellanos et al., 2022). However, in Guaviare, engaging in logging activities as an alternative use of the forest presents significant barriers for settlers and peasants due to the need for substantial initial investment and specialized technical knowledge. Consequently, there is a limited availability of economic alternatives stemming from forest resources compared to the production of livestock and short-cycle agricultural crops. In 2021, only two persistent harvesting permits, covering approximately 300 hectares, were issued for the natural forest within the department (CDA, 2022). To promote positive changes towards SFM, the CDA[11] has undertaken the development of a new persistent permit, encompassing an area of 6,291 hectares. By providing the necessary

[11] Corporation for the Sustainable Development of the North and East Amazon, CDA by its acronym in Spanish.

support and facilitating access to permits, the intention is to enhance economic opportunities derived from the forest resources while ensuring responsible management and conservation. Importantly, when the forest resource generates economic benefits, it reduces the likelihood of inhabitants seeking a change in land use to secure their subsistence (FAO, 2022).

2.2 Related literature

2.2.1 Estimating the growth of tropical forest species

In SFM, having knowledge of the forest species is crucial since they form the foundation of the business, representing its natural capital. The growth rate of the different species plays a key role in determining the maximum volume of timber that can be extracted from the forest as well as the appropriate cutting cycle. Indeed, the growth of forest species is commonly quantified by measuring the increase in the diameter of individual trees. This measurement serves as the basis for constructing growth curves, which require determining both the diameter growth rate[12] and the maximum diameter of the trees. By analyzing the growth curves and utilizing data from a forest inventory, it becomes possible to effectively plan the volume of timber to be extracted from the forest and estimate the time required for its regeneration.

Yet, constructing growth curves for tropical forest species is challenging due to the great variability among trees in terms of growth behavior and their response to edaphoclimatic conditions (Lieberman et al., 1985; Trouillier et al., 2020; Zhou et al., 2021; Scalon et al., 2022). It is important to emphasize that growth rings, which are typically reliable for estimating tree age, have limited value for age determination in non-seasonal environments like tropical regions. Even for species that exhibit well-defined rings, the relationship between age and ring formation remains uncertain and may vary among individuals, species, and sites (Lieberman et al., 1985; Trouillier et al., 2020).

One method commonly employed for constructing growth curves and determining cutting cycles in tropical areas is the use of "passing times", defined as the time required for an individual tree to pass from the lower limit of one diameter class to the upper limit of the same or from one diameter class to the next (Contreras, 1998; López and Tamarit, 2005). To

[12] In this case, the commercial height of the individual tree is averaged for each diametric class according to inventories carried out in the field. Thus, when a tree passes from one diameter to the next, its height will correspond to the value averaged for the new diametric class.

establish passing times for a specific tropical forest species, field measurements are required, and these measurements are typically collected from permanent sampling plots (Arets, 2005; Briemen and Zuidema, 2006; Barraza et al., 2015). The continuous measurements conducted in permanent sampling plots provide valuable information for monitoring changes in abundance, basal area, and volume of the forest, or of a group of species, and to determine growth rates, mortality, and recruitment. However, in the absence of permanent sampling plots to directly measure passing times of trees, we adapt an alternative methodology in Section 3. Our methodology aims to estimate the growth curves for the specific forest species of interest, taking into account the available data and resources in the study area.

2.2.2 Bioeconomic models for sustainable forest management

Bioeconomic models are analytical tools that integrate biophysical and economic models to analyze biological and economic changes caused by human activities. Both biophysical and economic components are developed based on historical observations or theoretical relationships, and the complexity of the model varies according to the equation systems, modeling activities, and the programming language used (Bobojonov, 2022). These types of models are applied in research on environmental externalities associated with policy reforms or the use of natural resources.

In the forestry sector, the economic aspect of managing renewable resources, particularly in terms of profitability and maximizing production, revolves around determining the optimum cutting cycle. Extensive research (Arosa, 1996; Touza-Montero and Termansen, 2001; Arias, 2013) highlights the crucial economic question of when to harvest trees to maximize the value of natural capital. This consideration takes account of factors like expected wood prices, harvesting costs, interest rates, productivity, as well as the growth rate, diameter, and height of different tree species. The principles of conservation and sustainability of natural resources must at the same time be prioritized.

Arias (2013) analyzed the Faustmann model as a valuable approach for maximizing the value of capital in a forest plot over an infinite succession of productive cycles. This model is commonly used to estimate optimal objectives for private profitability, particularly in the context of forest investments. It is applicable to forest plantations with homogeneous ages, which simplifies the calculations. However, the model has important limitations when it comes to its application in SFM, mainly because it does not include other ecological and economic aspects of forests, two of which, the value of other ecosystem services, and selective felling, are the basis of the SFM approach.

Maldonado (2008) introduces an alternative bioeconomic model for the management of mature forests as a non-renewable resource. This approach acknowledges that once a mature forest is harvested, it cannot be recovered within a feasible human-economic timeframe. The model is based on Conrad’s proposal (1999) for mature forests, according to which, depending on the total forest area, one section is destined for preservation and another for felling. Once felled, the latter no longer provides forest ecosystem services and its use changes. However, and in accordance with current Colombian legislation, this type of practice would not be viable in an SFM because persistent use is not compatible with land use change.

Holmes and Sills (2015) propose an alternative approach that offers more valuable analytical frameworks for evaluating SFM in the context of timber production. Their approach distinguishes between continuous time (CT) and discrete time (DT) models, which are used to optimize the utilization of natural tropical forests while considering various biological restrictions. These restrictions include the differentiated growth of forest species, the additional ecosystem services that can be affected by the use, and the well-being of resident communities. Within this literature, Castro et al. (2018) analyze the importance of bioeconomic modeling integrated with mathematical programming techniques and a holistic vision to support decision-making on land use. It underscores the significance of integrating variables such as social welfare and recognizing the trade-offs between land use and ecosystem services. By incorporating these aspects into the modeling process, a deeper understanding and predictive analysis of the anthropological and sociological dimensions of resource allocation can be achieved.

Important applications of CT bioeconomic models related to tropical forests are the contributions of Ehui and Hertel (1989), Barbier and Rauscher (1994), Kant (2000), Potts and Vincent (2007) and Kant and Shahi (2003). These studies evaluate the future costs and net present value of logging and its effects in deforestation. Matta et al. (2007) use a dynamic optimization model to assess the advantages and disadvantages of conservation and the economic costs of implementing lower-impact forestry practices. Their model incorporates the value of timber and non-timber products, and incentives for ecosystem services associated with each management regime to determine the economic profitability of forestry practices. Several discrete time (DT) bioeconomic models have been employed to evaluate the optimal harvesting intensity and net present value of timber resources. Notable studies in this field include works by Boot and Gullison (1995), Boscolo and Buongiorno (1997), Bach (1999), Boscolo and Vincent (2000), and Macpherson et al. (2012).

In our perspective, the main advantage of DT with respect to CT models is that the former allows multiple restrictions, or control variables, to be considered. They are thus better suited to SFM which must consider (i) various forest species with different volumes and growth rates, (ii) minimum cutting diameter, and (iii) maximum harvest volumes[13]. However, we remark that the availability and quality of data to specify the economic or biological parameters of these models pose a significant limitation. This constraint often hampers the interpretation and generalization of the results beyond the study area, as we will discuss in the next section.

3. Material and methods

3.1 Data collection and treatment

3.1.1 Biological information

To estimate the growth curves for the species of interest, we used data obtained from forest inventories and censuses of ten forest management plans. This information is accessible through the CDA (CDA, 2022). The collected data covers a timeframe ranging from 2017 to 2022 and includes several crucial parameters, such as: (i) location coordinates of the properties subjected to forestry use, (ii) area designated for forestry activities, (iii) volume of timber to be utilized, (iv) species targeted for exploitation, (v) dasometric data pertaining to the species being exploited, e.g., the diameter at breast height (DBH), total tree height, marketable height, and information on wood quality. Dasometric data represent the initial measurements of all individual trees and serve as the baseline measurement at a specific point in time, denoted by $t = 0$.

Since there will not be a second field measurement of the same tree individuals registered in the studies obtained from the CDA, the passing time of trees is derived from

[13] For the study area, the environmental authority restricts the use to a maximum of 70% of the available volume. In the model section these restrictions will be extended.

existing literature. Although trees may exhibit greater growth in smaller diameter classes, an equal mean increase is assumed for all size classes based on technical reports (see Table 1).

Moreover, our analysis considered additional assumptions derived from the forest management plans. These assumptions include: (i) Maximum age. The maximum age reached for each species is determined by the maximum diameters recorded in the field. Since there is no active intervention occurring in the studied forests, it is assumed that the field records capture the largest growth of each species in the area. (ii) Current stocks. The current stocks of forest species were considered in terms of volume and the average number of trees per hectare for each diameter class. These stocks represent the maximum volume that each species can reach in the study area and can be considered as the carrying capacity. (iii) Minimum cutting diameter. According to CDA mandates, the minimum cutting diameter has been set at 40cm DBH. Consequently, trees with a diameter smaller than 40cm will be exempt from any intervention. The smaller diameter classes represent the natural regeneration that is available to replenish the harvested volume, in combination with the remaining trees in each diameter class greater than 40cm after harvesting.

Based on the considerations and assumptions outlined above, the collected data were used to calculate the current maximum number of trees, basal area, and volume for each diameter class. The age of each tree is determined based on its diameter. With this information, growth curves were constructed, showing the average commercial volume per hectare for each diameter class based on the current stocks and age estimates derived from the time it takes for a tree to transition from one diameter class to the next. The growth curves are typically represented by DBH as a biological parameter and the volume is influenced by the form factor (FF) and the commercial height of the trees. The collected information allows for the estimation of these parameters based on measurements of DBH, commercial height, and FF of the trees recorded in the field. As such, it becomes possible to calculate the commercial volume for each diameter class in the study area and present growth curves in terms of volume. Table 1 provides a summary of constructed variables and the data utilized in each case.

Table 1. Constructed variables and available information.

Variable		Information source
Forestry variables. Baseline, t=0.	Diameter at Breast Height (DBH), in centimeters (cm).	Forest management plans, CDA (2022).
	Commercial height of trees, in meters (m).	
	Commercial volume by diameter class, in cubic meters (m^3).	
	Number of trees per hectare.	
Average diameter growth rate	Achapo (*Cedrelinga cateniformis*).	Average growth of 1cm DBH/year, Baluarte and Alvarez (2015).
	Cabuyo (*Eschweilera coriacea*).	Reported growth of 0.4cm/year, Tello (2011).
	Dormidero negro (*Parkia discolor*).	Average growths were taken for the genus Parkia of 0.5cm DBH/year, Panaifo (2019).
Species age	Age by diameter class, in years.	(Minimum class diameter in centimeters – 10) / Average annual increase in cm/year.
	Commercial volume by diameter class, in cubic meters (m^3).	Volume by diameter class of the FPM.
Restrictions	Maximum age of trees.	Maximum diameters shown in the forest management plans.
	Maximum volume per hectare and per diameter class (carrying capacity).	Average stocks per hectare according to forest management plans.

The processing of the field information involved the compilation and organization of data from the forest inventories and censuses of each forest management plan into a single Excel database. During this process, the consistency and uniformity of the measurement units were carefully reviewed. For example, it was ensured that all diameters and heights were in meters, and coordinates were in decimal format. For the specific study at hand, certain restrictions were applied. DBH measurements above three meters and heights above 60m were excluded for the three species. This exclusion was based on field information indicating that large-diameter specimens are often hollow, which would result in an overestimation of forest supply. The number of individuals exceeding these measurements was minimal, suggesting potential data input errors. Once the data was processed and cleaned, the entire database was reviewed, and the relevant data pertaining to the three species under study were selected for further analysis.

Upon reviewing the available information, it was found that there were ten harvest requests between 2017 and 2022, resulting in a total of 33,634 individuals with a diameter greater than 10cm. These individuals belonged to nearly 500 different species, as recorded in the inventories and censuses conducted during that period. Out of the total number of individuals, 12,165 were specifically requested for felling, with a corresponding volume of 24,365m^3. The three species under study accounted for approximately 30% of the total felled volume, highlighting their significance in the area (as shown in Table 2).

Table 2. Main forest species requested for forest use.

Species		Quantity	%	Volume (m^3)	%
Milpo	*Erisma uncinatum*	832	7%	3,283.09	13%
Achapo	***Cedrelinga cateniformis***	**729**	**6%**	**3,242.63**	**13%**
Dormidero negro	***Parkia discolor***	**609**	**5%**	**2,159.24**	**9%**
Cabuyo	***Eschweilera coriacea***	**2,101**	**17%**	**2,051.86**	**8%**
Dormidero	*Parkia multijuga*	173	1%	1,427.47	6%
Parature	*Goupia glabra*	476	4%	1,350.07	6%
Arenillo negro	*nn**	659	5%	1,068.54	4%
Macano negro	*nn*	203	2%	943.40	4%
Arracacho	*nn*	443	4%	721.55	3%
Algarrobo	*Hymenaea oblongifolia*	372	3%	702.85	3%
Other species	*nn*	5,568		7,414.08	30%
Total		**12,165**	**54%**	**24,364.78**	**100%**

Source: Forest management plans (CDA, 2022).

* The species reported with "nn" (No Name) do not have taxonomic identification in the reviewed studies.

3.1.2 Economic information

The data concerning income and exploitation costs of timber products were obtained from secondary sources, like ONFA and EFI (2019), ONFA and GGGI (2021), and GIZ, PROBOSQUES and ONFA (2022). These studies provide valuable insights into the financial aspects of timber product extraction. The data from these studies were used as inputs in our bioeconomic model, which will be discussed in the subsequent section.

Table 3. Income and marketing costs for the three commercial species under study.

Item	Total price, in Colombian Pesos (COP)	COP/m³	Fixed costs	Variable costs		
				Cedrelinga	Eschweilera	Parkia
Annual technical assistance	147,228,581	56,539				
Forest management plan and other annual costs	109,808,100	2,100	109,808,100			
Opportunity cost of land, in COP/ha	10,000	922	60,000,000			
Cost of roads (construction and maintenance)	204,000,000	3,901	204,000,000			
Harvesting cost	135,200	135,200		135,200	202,800	135,200
Minor Transport (animal Force)	150,000	150,000		150,000	150,000	150,000
Major transportation to Villavicencio city		333,604		333,604		333,604
Taxes and other costs						
Administration	2%			2%		
Silvicultural management measures	6,228,140	2,392	155.703.500			
Compensatory rate for forest exploitation (CRFE)				97,135	60,761	97,135
Costs		**706,553**	**529,511,600**	**715,939**	**413,561**	**715,939**
Market price (COP/m³ block wood)				**1,000,000**	**533,280**	**1,000,000**
Profit before fixed cost for m³ of block wood				**284,061**	**119,719**	**284,061**

Source: Calculated from (GIZ, PROBOSQUES and ONFA, 2022), (ONFA and EFI, 2019), and (ONFA and GGGI, 2021).

The cost items presented in Table 3 correspond to management plans for large areas, specifically 6,291 hectares in the case of Guaviare. These management plans typically have cutting cycles ranging from 20 to 25 years. It contrasts with the traditional forest use practices in Colombia, where smaller management areas, usually ranging from 200 to 400 hectares, are common, and the maximum time for harvesting varies from one to three years (ONFA and EFI, 2019; CDA, 2022). The sale prices considered for the Cabuyo (*Eschweilera coriacea*) species were based on roadside prices in Guaviare, while for the other two species, the prices were based on warehouse prices in Villavicencio city[14]. The decision to use warehouse prices in Villavicencio for the latter two species was based on the fact that the market offers better prices, which justifies the additional investment in transportation for their mobilization. However, for the case of Cabuyo, the prices paid for its timber products in Villavicencio do not adequately compensate for the additional investment required for transportation.

The fixed costs considered in the analysis include the costs associated with forest management plans, the opportunity cost of land, and the construction and adaptation of roads. These costs are classified as fixed since they remain constant regardless of the volume of timber used. In other words, the user must bear the same costs of the forest management plan, whether they utilize $1m^3$ or the maximum authorized volume of $25m^3$ per hectare, as specified by the CDA. For modeling purposes, these fixed costs are entered per hectare. On the other hand, variable costs only apply to each cubic meter of timber utilized. The data presented in Table 3 represents estimates for the exploitation and sale of block wood. To align these costs with the model, they have been converted to costs per cubic meter of standing timber using the transformation factor provided by the CDA[15], which corresponds to 50%. By standardizing the costs per cubic meter of standing timber, the model can accurately capture the financial implications of timber extraction and assess the profitability of different scenarios.

3.2 The bioeconomic model

We develop a DT bioeconomic model aimed at optimizing the utilization of timber products derived from the forest species under investigation. Concretely, the model estimates the optimal combination of the volume to be extracted and the time required for its replacement (cutting cycle), which allows maximizing the economic benefit considering biological restrictions. For the optimization process, the model considers: (i) the stock available in the forest, (ii) the average growth of the species, (iii) the volume to extract, (iv) extraction costs, and (v) a discount rate[16] that is applied to natural capital to value its future benefits. The objective function (Holmes and Sills, 2015) is described as follows

[14] Villavicencio is the city with the closest collection center to Guaviare, with a good market for timber products.
[15] It is estimated that there is a waste of wood during the transformation process from trees to wood in simple squared blocks. The CDA utilizes a transformation factor of 50% for this estimation.
[16] It also allows consideration of the ecosystem services provided by the forests.

$$\max NPV = \sum_{t=0}^{T} \frac{1}{(1+r)^t} \left[\sum_i (P_i - C) h_{it} - F \right] , \qquad (1)$$

where $\max NPV$, maximum net present value, denotes the maximum net benefit from harvesting, T the planning time horizon, r the discrete annual discount rate, P_i the market value of timber for the species i, C the variable cost of harvesting, F the fixed cost of harvesting, and h_{it} the volume to be harvested for the species i in time t. Calculating the NPV, or expected land value over a finite time horizon, derived from logging requires the analyst to assign a value to the time preference rate. Unlike CT models specified from the perspective of a social planner who may use a low or decreasing social discount rate, DT bioeconomic models typically use a constant rate of time preference that reflects general business conditions.

Equation 1 specifies the time period for the economic analysis to extend from the present ($t = 0$) until some specific finite period in the future ($t = T << \infty$). This specification is used when the analyst is interested in the economic returns of a few cutting cycles. Although it is possible to extend the analysis into the future, $T < t$, a constant exponential discount rate will make the economic benefits received after several cutting cycles empirically trivial. Equation 1 also allows for anticipated changes in timber prices or costs to be included if information is available to guide that decision. In this study, for analytical simplicity, P_i, C and F are kept constant.

To model the dynamics of the natural resource and its optimal felling, matrix transition rules were defined based on the stocks by diameter class of the three species and the passing times of trees. The number of trees that pass from one diameter class to another depends on the stock in each class recorded in the field data and the estimated average growth rates based on literature review. Recruitment, that is, the number of trees entering the tree class 40cm of DBH, is estimated according to the number of remaining trees, i.e., less than 40cm of DBH. These assumptions suggest that silvicultural management practices guarantee that the natural regeneration of forests is not affected, such that the stock of trees less than 40cm of DBH are sufficient for recruitment. Using matrix notation, the dynamics of the natural resource can be represented as follows

$$n^{t+k} = A^k \mathbf{n}^t \quad , \tag{2}$$

where $\mathbf{n} = (n_j)_{1\le j\le m}$ is the abundance vector whose elements are the number of trees, $n_j \in \mathbb{R}_{\ge 0}$, in each diameter class, $j \in [1, m]$. The parameter $m \in \mathbb{R}_+$ represents the number of diameter classes, and k is the time, $t = 1 < k \le T << \infty$. The matrix A represents the matrix of $m \times m$ transition rates between diameter classes, where $a_{uv} \in \mathbb{R}_{\ge 0}$, $1 \le u, v \le m$.

Harvest is evaluated based on matrix dynamics to estimate the effect of removing different numbers of trees of each class and diameter on the growth of remaining trees. In this way, formulation 2 is modified as

$$n^{t+k} = SA^k \mathbf{n}^t \ , \tag{3}$$

where S is a diagonal matrix, i.e., $S = diag(s)$ and $\mathbf{s} = (s_j)_{1\le j\le m}$, therefore, $\forall j \in [1, m]$, $s_j \le n_j$. In this case S represents the remaining trees of each diameter class and, $\forall j \in [1, m]$, $\mathrm{h}_j = n_j - s_j$ represents the number of felled trees (harvest) for each diameter class. In addition to these biological growth and yield functions, other conditions are used to specify logical constraints, e.g., specifying harvests of trees that exceed a diameter limit. Hence, to ensure SFM, not only are diameters restricted to a minimum usable size of 40cm, but the volume of harvest is also limited to a maximum of 70% of the existing stock, based on the regulations of the environmental authority adopted in the terms of reference for the preparation of forest management plans (CDA, 2017). Mathematically, $\mathrm{h}_{j\in\{1,2,3\}} = 0$ and $0 \le \mathrm{h}_{j\in\{4,\ldots,m\}} \le 0.7 n_j$.

4. Results and discussion

This section shows, first, the results of the growth curves for the three commercial forest species under investigation and, second, the results derived from the bioeconomic model for optimization of forest use.

4.1 Growth curves of tropical forest species

Table 4 shows a summary of the field data used, in terms of volume by diameter class. The growth curves are shown in Figures 3, 4 and 5. To calculate the growth curves of the species, the data shown in Table 4 were adjusted with third-order polynomial regressions. The polynomial of order three of the adjustment functions represents the evolution of the volumes of the species, expressed in cubic meters (m^3), in the time. The setting function, $V_i(t)$, for each species i, is presented in the captions of Figures 3-5. Achapo (*Cedrelinga cateniformis*) is the fastest growing species, reaching an increase of 1cm in diameter of DBH/year (Baluarte and Alvarez, 2015). The species achieves its maximum commercial volume in the diameter class of 90 to 100cm, in an approximate time of 80 years. Cabuyo (*Eschweilera coriacea*) has the lowest growth rate reported, of 0.4cm/year (Tello, 2011) and reaches the largest volumes in the 40 to 50cm diameter class, in an approximate time of 66 years. Dormidero negro (*Parkia discolor*) average growths were taken for the genus *Parkia* of 0.5cm of DBH/year (Panaifo, 2019). According to field data, the species reaches the largest volumes in the 80 to 90cm diameter class, in an estimated time of 140 years.

As part of the adjustment analyses, several trials were carried out in the construction of these curves, based on the availability of data from the forest management plans. The results that presented the best adjustment were the curves constructed from the information of a single forest management plan, corresponding to the one carried out on the countryside[17] Puerto Cubarro and Puerto Polaco in the municipality of Calamar (Cooagroitilla and ONFA, 2021). The field data are those shown in Table 4. In the different adjustments made, the curves generated with the data of the ten forest management plans lost quality to fit despite having more information. As mentioned by Holmes and Sills (2015), this could be because population matrix models are based on the assumption that transition probabilities are stable over time, so these models cannot take into account effects of different sites, stand structures, or competitive conditions. In this case, it is clear that the model only applies to the area where the data was recorded. Notice that the remaining forest management plans correspond to smaller areas, and this implies less information and greater variability in the data, which may influence the results obtained.

[17] The villages are territorial divisions of an administrative nature in the rural area of the municipalities, established by municipal agreement (DANE, 2018).

Table 4. Volume (m^3) by diameter class and by species for 219 registered hectares.

Class Diameter (cm)	10-<20	20-<30	30-<40	40-<50	50-<60	60-<70	70-<80	80-<90	90-<100	100-<110	110-<120	120-<130	130-<140	140-<150	150-<160	160-<170	170-<180	180-< 190	> 190	Total
Achapo (*Cedrelinga cateniformis*)																				
Vol (m^3)	3.02	7.30	27.40	42.33	29.45	64.35	60.23	61.17	167.38	84.88	61.90	116.7	65.46	203.1	47.53	88.01	33.99			1,164
m^3/ha	0.01	0.03	0.13	0.19	0.13	0.29	0.28	0.28	0.76	0.39	0.28	0.53	0.30	0.93	0.22	0.40	0.16	0.0	0.0	5.32
Years	-	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	-	
Cabuyo (*Eschweilera coriacea*)																				
Vol (m^3)	41.48	145.27	287.10	466.15	398.09	327.19	178.82	71.15	48.26	28.04	11.10	7.86	13.94		28.45					2,053
m^3/ha	0.19	0.66	1.31	2.13	1.82	1.49	0.82	0.32	0.22	0.13	0.05	0.04	0.06	0.00	0.13					9.37
Years	0	22	44	66	88	110	132	154	176	198	220	242	264	286	308					
Dormidero negro (*Parkia discolor*)																				
Vol (m^3)	4.23	20.03	26.56	59.96	66.67	107.25	86.86	138.41	103.45	125.56	69.12	80.52	45.47	51.75	16.08	29.79	37.80		73,2	1,143
m^3/ha	0.02	0.09	0.12	0.27	0.30	0.49	0.40	0.63	0.47	0.57	0.32	0.37	0.21	0.24	0.07	0.14	0.17	0.0	0,33	5.22
Years	0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360	

Source: Estimates of the study based on the forest management plan of Cooagroitilla (Cooagroitilla and ONFA, 2021).

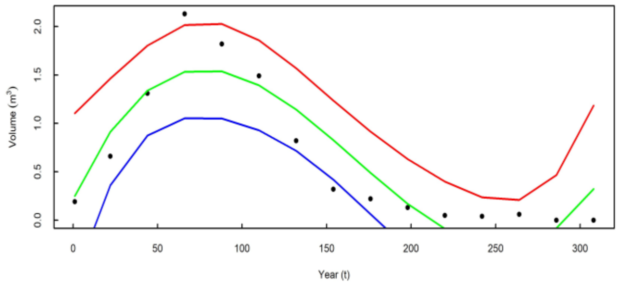

Figure 3. Growth curve for Cabuyo (*Eschweilera coriacea*).

Minimum growth — Medium — Maximum

The setting function is

$$V_E = 0.2357 + (3.82e-02)t - (3.23e-04)t^2 + (6.49e-07)t^3$$

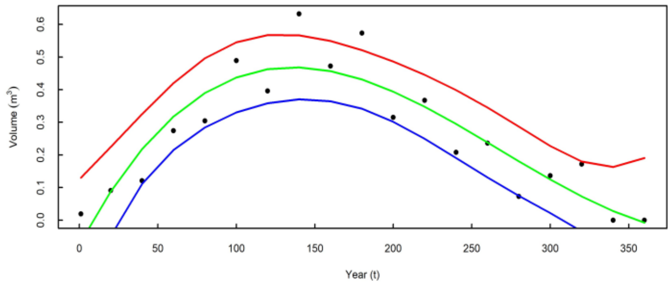

Figure 4. Growth curve for Dormidero negro (*Parkia discolor*).

Minimum growth — Medium — Maximum

The setting function is

$$V_P = -0.069 + (8.88e-03)t - (4.36e-05)t^2 + (5.39e-08)t^3$$

Source: Study estimates based on field data (Table 4) and Tello (2011).

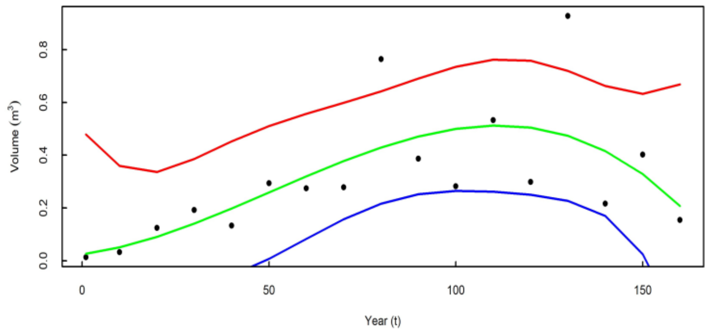

Figure 5. Growth curve for Achapo (*Cedrelinga cateniformis*).

Minimum growth Medium Maximum

The setting function is

$$V_A = 0.0264 + 0.0018t + (9e-05)t^2 - (6e-07)t^3$$

Source: Study estimates based on field data (Table 4) and Baluarte and Alvarez (2015).

4.2 Optimal modeling solution

The model presented in Section 3.2 was developed using R software (R Core Team, 2020). Additional variables were considered, such as a discount rate of $r = 0.08$ [18], the maximum use of up to 70% of the volume available by diameter class, starting from the fourth class (trees of 40cm DBH), i.e., $0 \le h_{j\in\{4,\ldots,m\}} \le 0.7n_j$ with $h_{j\in\{1,2,3\}} = 0$, and planning horizon $T = 50$ years. The results obtained are shown in Table 5 and Figure 6. The total volume to be extracted is 16.56 m^3, equivalent to 95% of the available volume, in a planning horizon of 50 years, which suggests that less than 50% is extracted in each cutting cycle.

Table 5. Optimum cutting cycle, volume, and estimated benefit for the three selected forest species in Guaviare.

Species	Available volume (m^3/ha $\geq$ 40cm)	Total extracted volume (m^3/ha)	Total benefit COP/ha	Optimum cutting cycle (years)
Achapo (*Cedrelinga cateniformis*)	5.14	4.85	855,596	25

[18] This is the discount rate used by the United States Forest Service (USAID) in the practical evaluation of its tool for the simplified financial analysis of forestry initiatives "Green Value tool" in community forestry initiatives in Colombia.

Species	Available volume (m^3/ha $\geq$ 40cm)	Total extracted volume (m^3/ha)	Total benefit COP/ha	Optimum cutting cycle (years)
Cabuyo (*Eschweilera coriacea*)	7.21	7.19	379,552	
Dormidero negro (*Parkia discolor*)	4.98	4.51	763,892	
Total	**17.33**	**16.56**	**1,999,040**	**25**

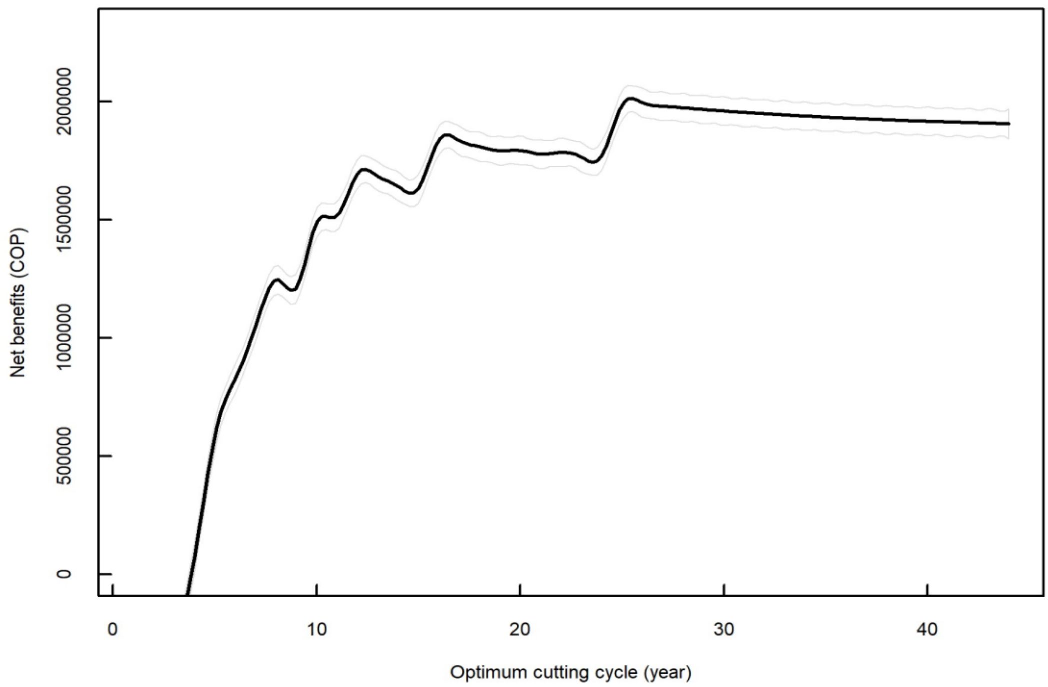

Figure 6. Determination of the optimum cutting cycle, in years, for a planning horizon of 50 years.

4.3 Sensitivity Analysis

The sensitivity analysis examines the model results by assessing the impact of variables like harvesting costs and species sale prices, which directly impact the income received. The impact on the results of the variation in the discount rate and the growth assumptions of forest species was also evaluated, as biological assumptions of the model.

The sensitivity analysis was based on all these variables since they are the most important ones in the model. The wood transformation factor directly affects costs and income, and therefore its impact is considered when analyzing the latter. Additionally, this transformation factor is defined by the environmental authority, a situation that prevents its variation as part of the analysis.

The results of the sensitivity analysis showed that both the increase in costs and the decrease in sales prices affect the net benefits shown by the model but have no impact on the determination of the optimum cutting cycle, as can be seen in Table 6. Likewise, it is observed that the use is more sensitive to the decrease in income since a decrease of 10% impacts the net benefit by 30%; while a 10% increase in costs impacts the benefit by 19%.

The analysis of the discount rate showed that a change in this variable from 8% to 12% decreases benefits by 32%, going from COP 1,999,040 (USD 498.3) per hectare to COP 1,558,542 (USD 388.5). At the same time this shortens the optimal period from 25 to 16 years (Table 6), prioritizing the interest in obtaining income in less time, but not necessarily the future value of the forests. When this rate is reduced to 3%, the net benefits increase, but the optimal cutting cycle increases from 25 to 33 years. In the latter case, the future value of the natural resource is prioritized, sacrificing economic benefits, since more time is required for the financial return.

Table 6. Sensitivity analysis.

Analysis variable	Net profit (in COP)	Cutting cycle (years)
Interest rate $r = 0.12$	1,558,542	16
Interest rate $r = 0.03$	2,293,815	33
10% increase in costs	1,618,197	25
10% decrease in revenue	1,390,051	25

The sensitivity analysis on the growth of the species evaluates one of the strongest assumptions of the model, since, as stated, the forest is the natural capital in SFM. The sensitivity of the model was evaluated assuming a 50% decrease in the rates of diametric growth consulted in the literature, which supposes that Achapo decreases its diameter growth rate from 1cm to 0.5cm in DBH/year, whereby it would reach its maximum commercial volume in the diametric class of 90 to 100cm, in an approximate time of 160 years. The reported growth rate of the Cabuyo decreases from 0.4 to 0.2cm DBH/year, reaching the largest volumes in the 40 to 50cm diameter class, in an approximate time of 132 years, and

Dormidero negro reduces its diameter growth rate from 0.5cm to 0.25cm DBH/year, whereby this species reaches the largest volumes in the 80 to 90cm diameter class, in an estimated time of 280 years.

The results of this analysis, shown in Figure 7 and Table 7, indicate that a decrease in growth rates decreases the maximum volume to be extracted and increases the optimum cutting cycle, with a negative impact of 33.5% on net benefits, which go from COP 1,999,040 (USD 498.3) to COP 1,330,169 (USD 331.5). With these results, it can be seen that the model seeks to guarantee the sustainability of the resource, understanding that with slower growth rates, more time is required for the forest to recover (increase in harvest cycle). Likewise, the decrease in the volume to be extracted increases the number of remaining trees, which in turn positively impacts the replacement capacity of the resource. According to the results shown in Table 7, the species Dormidero negro and Achapo have a greater impact in terms of the volume to be extracted, which decreases by 26% and 27%. For the Cabuyo the impact is 15%. These results can be attributed to the available volume, which is greater in the case of Cabuyo and being the species with the lowest growth rate, its real impact on the diameter growth is less than that of the other two species.

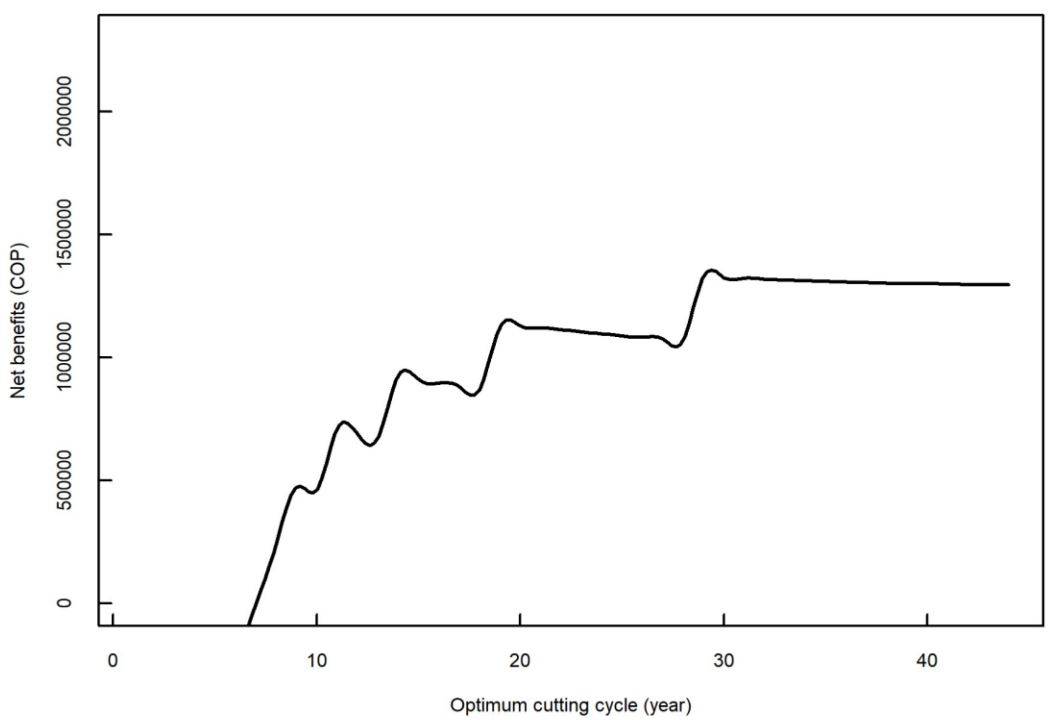

Figure 7. Determination of the optimum cutting cycle, in years, for a planning horizon of 50 years, reducing the growth rates of the species under study by 50%.

Table 7. Optimum cutting cycle, volume, and estimated benefit for the three selected forest species, decreasing their growth rates, in Guaviare.

Species	Available volume (m^3/ha $\geq$ 40 cm)	Total extracted volume (m^3/ha)			Total benefit (COP/ha)		Optimum cutting cycle (years)	
		Base line	Reducing growth rate		Base line	Reducing growth rate	Base line	Reducing growth rate
			m^3/ha	%				
Achapo (*Cedrelinga cateniformis*)	5.14	4.85	3.56	17%	855,596	568,418	25	29
Cabuyo (*Eschweilera coriacea*)	7.21	7.19	6.12	15%	379,552	268,439		
Dormidero negro (*Parkia discolor*)	4.98	4.51	3.32	16%	763,892	493,312		
Total	**17.33**	**16.55**	**13**	**21%**	**1,999,040**	**1,330,169**	**25**	**29**

4.4 Discussion of the results

A comparative analysis of our results with the current situation in Guaviare identifies several options for improvement: (i) cutting cycles and extraction rates, (ii) natural regeneration, (iii) net economic benefit, and (iv) monitoring.

(i) Cutting cycles and extraction rates. Within a planning horizon of 50 years, we obtain that the optimum cutting cycle can be divided into two harvests, each involving the extraction of slightly less than 50% of the available volume for each species. This value is lower than that established by the environmental authority's regulation, which authorizes the use of up to 70% of the volume available in each diameter class, for any species in a single cutting cycle, provided that the volume per hectare for the total number of species requested does not exceed 25m^3. The environmental authority applies these restrictions to guarantee forest sustainability, however, these amounts are not based on scientific research that defines the optimal harvesting conditions for the species used in the study area. Notice that legislated utilization percentages of 70% of the available volume may imply less remaining volume and, therefore, less renewability. Moreover, the cutting cycles requested in the forest management plans for persistent use in the region are less than ten years, aligning with the provisions of the country's natural resources code[19]. As shown, such short cutting cycles do not allow sufficient time for the replenishment of forest resources, resulting in unsustainable forest management practices. Our findings suggest a revision of national legislation to ensure SFM. The forest management plan of Cooagroitilla (Cooagroitilla and ONFA, 2021), which constitutes the final basis for the estimation of the growth curves in this study, proposes a harvest period of 25 years[20] and an area sufficient for the beneficiaries to have 25 annual cutting units (ACU). By aligning with the renewal capacity of forests, we argue that this approach is better positioned to foster local economic development while promoting SFM.

(ii) Natural regeneration. In volumetric terms, our results suggest that, of the 17.33 m^3 available for harvesting, the forest would be able to renew 16.55 m^3; taking account of the existing volume in the diameter classes less than 40cm of DBH, the remaining volume of classes greater than 40cm, and the growth curves constructed for three commercial species. This result is relevant since it shows the viability of a SFM that is based on selective exploitation without changing the use of land and without affecting the normal yield of the forest, a premise that would be fulfilled by these results. In construction of the model, it was clear that the protection of young diameter classes guarantees renewal of the volume necessary for the use of the next harvest. Considering the significant harvest intervention of mature trees, it becomes crucial to analyze the potential negative impacts on seed production and natural regeneration. By doing so, the planners can mitigate the risk of depleting sapling stocks and ensure continuous recruitment. Negative impacts can also be minimized with the introduction of post-harvesting silvicultural management, considered as part of the projected costs in the SFM. Indeed, SFM should give particular emphasis to the careful management of natural regeneration of both the exploited species and others. It is expected, though, that SFM will stimulate the regeneration of natural forests, such that the remaining trees will have faster growth rates than those reported in the literature, as an effect of use, as shown by reviewed studies (Yue et al., 2022; Facciano et al., 2022). If this premise is met, the model estimates would be sufficient to guarantee the renewal of the resource. However, if average growths were lower than those utilized, the model should be adjusted to obtain the optimum

[19] Decree Law 2811 of 1974, included in Decree 1076 of 2015.

[20] This forest management plan proposes a cutting cycle greater than the 10 years regulated in the persistent use, thanks to a figure of association contract for vacant land, which allows this management. It coincides with the guidelines for the Brazilian Amazon, which recommend harvest cycles between 25 and 30 years for natural tropical forests (Bomfim et al., 2021).

cutting cycle and not affect forest sustainability. In this regard, our sensitivity analysis shows that decreasing average growth rates of species would necessitate increasing the harvesting cycle and decreasing the volume of felling to avoid negative impacts on forests. In the case of Guaviare, we expect that the growth rates of species after harvesting would exceed those documented in the existing literature. This assumption is based on SINCHI[21] (Giraldo et al., 2013) which reports increases of up to 2cm DBH/year for Achapo. Yet, these studies did not report findings for the other two species for which there is no exact data.

(iii) Net economic benefit. Our results show a net benefit of close to two million Colombian pesos (USD 498.3) per hectare for the considered planning horizon. The model estimates a higher net benefit in the first cut, equivalent to COP 1,159,443 (USD 289), and COP 839,597 (USD 209.3) in the second cut, with an optimum cutting cycle of 25 years. For this exercise are the sale of wood in the first degree of transformation, e.g., blocks sawn with a chainsaw. Economic benefits could be increased by introducing added value and selling products with a higher degree of transformation or of better quality. In the same way an increase in production costs, expenses not considered, or those unforeseen can decrease the net benefits shown in the optimization. The forest management plan of Cooagroitilla (Cooagroitilla and ONFA, 2021) proposes a usable forest area of 4,817 hectares and 23 beneficiary households, with an estimate of three to five members per household. For the first cutting cycle, we estimate that an average monthly income per household of COP 782,349 (USD 195) could be obtained during the 25 years, maintaining all the proposed variables, for the three species studied. These estimates do not include employment and gross income that could boost the economy of the region. Notice that our results are based on the analysis of only three commercial species. It is therefore possible that these findings vary when including a greater number of species targeted for logging. Concretely, the economic benefits derived from our optimization are expected to be higher when considering the total number of species projected as part of the SFM[22]. Opportunity costs were not evaluated in this study. However, research in the Amazon region shows that livestock activity, the main economic activity, reports an income of COP 235,000 (USD 58.6) per hectare for dual-purpose livestock (GIZ, PROBOSQUES and ONFA, 2022). This calculation does not

[21] Amazon Research Institute (SINCHI, abbreviation in Spanish).
[22] The forest management plan of Cooagroitilla (Cooagroitilla and ONFA, 2021) proposes the use of 12 forest species, of which the three species under study represent an important volume.

consider the cost associated with the loss of ecosystem services and other negative impacts from the felling of the forest for livestock farming. The sensitivity analysis showed that results from optimization are highly sensitive to changes in costs and revenue. Annual profitability depends largely on operational and financial management to guarantee efficiency in exploitation and support for better market options. Considering that communities in the post-conflict zone generally do not have business experience, coaching and training of these communities is necessary to ensure benefits.

(iv) Monitoring. The discount rate impacts the optimum cutting cycle estimated by the model, a result directly related to value of the resource. In this case, a short cycle allows the extraction of the greatest number of resources, sacrificing the time necessary for natural regeneration of forests. Unfortunately, our sensitivity analysis cannot be applied to natural regeneration. As described in the methodology, the growth curves of the species are based on a single measurement and a given increment assumption, which allows estimating passage times of trees. In this context, there is not enough information to analyze in deep how forest exploitation will affect regeneration capacity. To address this limitation, continuous monitoring of harvesting activities is important. By closely observing the behavior and characteristics of natural regeneration, valuable data can be gathered and integrated into the model, allowing for appropriate adjustments to be made. On the other hand, if the assumption of regeneration proposed for the model is not met, the volume for the next cutting cycle will not be guaranteed which will threaten the existence of the species being exploited. Thus, monitoring of the forest once it has been used must be included to guarantee its sustainability. In the event that monitoring shows insufficient regeneration, harvesting should be reconsidered.

5. Conclusion

This study shows that SFM can generate positive net benefits while maintaining the environmental restrictions that seek to preserve the normal yield of forests. However, it is observed that SFM is very sensitive to the interannual variation of costs and income, with profit margins that might seem low in terms of net economic benefits, but that represent a high impact in terms of gross economic income and generation of employment, much higher than livestock activities (GIZ, PROBOSQUES and ONZA, 2022). We suggest additional strategies to maximize the benefits derived from implementing SFM approaches in natural forests: (i) obtaining additional income associated with the voluntary market for carbon credits, as suggested by Bomfim et al. (2021); (ii) payment for ecosystem services associated with SFM projects, which represent market-based mechanisms to internalize the negative externalities associated with deforestation or to subsidize the positive externalities associated with SFM; and (iii) differentiated tax management, like the compensatory rate for forest exploitation, or some income tax exemptions. Methodologies for the carbon credit market associated with SFM have not yet been adopted in Colombia, nor have the strategies for the implementation of other economic incentives been developed. Therefore, the government could strengthen these aspects, sending a clear message on the conservation of forests and the improvement of the quality of life of the communities that inhabit them. Our results suggest that SFM is an economically and environmentally viable forest management option, with wide application in tropical regions like Guaviare. Yet, its success requires improvement in the political and regulatory framework and ongoing research on the forest species subject to SFM to generate good quality data to ensure a technical basis for SFM to promote forest sustainability.

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Conflicts of interest

The authors declare no conflict of interest.

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