

Article

Optimal Rotation and Ecosystem Services: A Generalization in Forest Plantations

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Abstract: Integrating different ecosystem services (ES) to determine when to harvest a forest stand is still challenging. This is due to the difficulty of obtaining information, models, and methods to quantify those ES and achieving an adequate valuation of these services. In this study, we propose a methodology comprising two different models that could allow for different ES integration with the optimal silviculture to calculate the optimal economic rotation. We have applied both models to eucalyptus plantations in Brazil considering two ES: wood with four different assortments and carbon sequestration. For both models, we calculated a ranking with previously defined management alternatives, with decreasing trees-per-hectare compared to traditional plantations. For the first model, when the ES are measured in monetary units, the optimal rotation corresponds to fewer trees per hectare than the traditional plantations and greater associated profitability. The second model incorporates the ES in physical units through a multi-criteria decision-making model and results in a longer rotation with again fewer trees per hectare. This study suggests that optimum forest rotation analysis should consider ES other than timber production integrated with silvicultural alternatives, such as spacing.

Keywords: multiple use; carbon sequestration; Faustmann formula; optimal stand management; goal programming



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1. Introduction

It has long been recognized that determining the optimal economic rotation at the forest stand level is a fundamental aspect of forest economics. From early and seminal studies [1,2], an extensive and precise literature has been developed covering different extensions of this inspirational idea [3,4]. Moreover, it continues to be a topic of interest, as evidenced by recent reviews [5].

Much of this literature, especially in its early stages, was characterized by considering only one ecosystem service (ES): wood production. In recent decades, however, there have been efforts to consider a broader set of ES in forest management. This premise has been integrated into the economic optimal forest rotation idea since a well-known paper which incorporated first some public goods provided by forests, such as amenity services [6]. In most cases, this integration was done by adding another ecosystem service, as pioneering studies on carbon sequestration have shown [7]. However, while other studies have made a clear distinction between different production functions for each ES [8,9], it was more common to consider a single production function that simultaneously provided more than one ES [10]. There was a lack of exploration into stand structure and the

corresponding management that could potentially optimize an ES other than timber. Some recent papers offer a different perspective [11,12], although they put forward hypotheses and methodologies different from those used in our study.

In forestry literature, the concept of multiple use is often considered synonymous with joint production [13,14]. However, other authors have pointed out that this equivalence had yet to be traditionally considered [15]. On the other hand, other authors offer a broader perspective on the concept of joint production, suggesting that provisioning and regulation ecosystem services are produced jointly [16]. It seems fair to assume that other ecosystem services are automatically generated when a provisioning ecosystem service is produced, as in the case of timber. Thus, it is widely assumed that all outputs associated with a forest system are produced jointly [17]. However, this does not necessarily imply that they are provided in fixed proportions [18]. However, it is essential to assume that some ES have a market price, and others do not.

It is becoming increasingly clear that forest systems provide a wide set of ES. However, there is still much to learn about how to manage them effectively. For example, we need to understand more about how to manage multiple ES simultaneously [19] and more precise information on both their production function and the results of their economic valuation [20], especially if they are not provisioning ES. Furthermore, it is not only that the value estimate is unknown, but also that there is sometimes uncertainty about when to start accounting for the existence of a particular ES in a plantation. An example of this could be the presence of a certain mycological production from a determined age of a plantation, even though it may not have been the initial objective of their management [21]. It is also worth noting that management objectives have evolved over time. While several of the classic studies cited above assumed that the monetary return received by the owner had to be optimized, it may be advisable to consider seeking other optima different from the private optimum considering the integration of other ES [10,22].

Among the different ES, carbon sequestration has been the subject of considerable attention for several decades. Indeed, since some influential papers [7,23], a large body of literature has been generated in this regard. As is well known, forest management affects the carbon balance and the supply of wood products [24]. On the other hand, the continuous changes related to supranational agreements guiding the adoption of policies to mitigate and reduce GHG emissions and the lack of a single global carbon market/standard, have led to the emergence of numerous approaches to the problem we need to consider. For example, when forest carbon is examined in the context of voluntary carbon markets, a variety of scenarios emerge depending on the specific protocol considered [25,26].

The examination of this aspect has seemingly necessitated a reconsideration of a tacit assumption present in all prior studies concerning the calculation of optimal forest rotation that excluded this ES: specifically, the length of the planning horizon. The horizon considered to define the optimal rotation ends when the stand is harvested. However, if the carbon sequestration is considered in wood products, the re-emission of this carbon occurs beyond this threshold [27], which could potentially complicate the analysis.

The main objective of this study is to present a methodology for integrating other ES into the calculation of the economic optimal forest rotation. This methodology considers both the optimal production function for each ES and the preferences of the decision-maker. The novelty of this research lies in its integration of various ES and silvicultural alternatives, while also considering the preferences of managers or decision-makers regarding each ES. Furthermore, it introduces a model that facilitates the inclusion of diverse ES in the analysis, even when they are not quantified in monetary terms. We propose that this development be carried out in a case study of a eucalyptus plantation in Brazil. In this case,

the methodology would integrate the analysis of two ES: timber (including various wood products) as a provisioning ES, and carbon sequestration as a regulation ES.

2. Materials and Methods

In order to frame the problem correctly, it would be beneficial to explain in detail the possible interactions between the ES involved, as well as the assumptions to be modified concerning the classical studies on optimal forest rotation. This information will be reflected in the proposed modeling, which is explained below.

2.1. Joint Production

It is evident that a single production process, such as stand growth, can result in multiple outputs within the forestry context. In other words, this process can be characterized as a joint production, given the existence of biological and/or economic interdependencies [28]. Therefore, it is not possible to represent this process by separate production functions, with one function representing each ES [18]. Consequently, there will be some costs that cannot be univocally assigned to each ES [29]. Costs allocation will require the implementation of specific procedures [30]. Setting aside the input classifications, it is evident that each ES will have an optimal level of capital and other inputs associated with it in a forest plantation. Furthermore, just as a landowner is unaware of the economic value of all the ES present on his property, he is also unaware of the relationships between stand growth and the different ES.

This ultimately implies that not all information is available when making fundamental decisions to determine the optimal rotation. Nevertheless, this does not preclude the possibility of making decisions with the available information, provided that a few assumptions are considered when making this decision. The initial capital is typically regarded as a fixed factor, given the direct relationship between outputs and the initial level of capital. This will affect all ES equally and only undergoes change at the rotation age [18]. This idea suggests that the initial planting density may vary depending on the selected ES.

The second assumption is that not all ES are typically regarded as being of equal importance. A great number of studies have assigned greater weight to wood products, yet the option of assigning different weights to each ES is not typically considered when defining the optimal rotation. Conversely, it is usually acknowledged that the various ES under consideration exhibit synergistic relationships, although exceptions may exist. Under this umbrella, some authors discuss the concept of additive ES [31]. In summary, determining the optimal forest management that considers multiple outputs is a complex undertaking [32]. In the context of forest plantations, the initial step would be to calculate the optimal rotation period for this joint production process [33].

2.2. Initial Conditions

Classical studies on the determination of the optimal rotation included a set of initial conditions that, implicitly or explicitly, were considered in this type of analysis. However, in a context of multiple use, some of these factors will not be considered in the present study. Table 1 illustrates the initial assumptions typically (though not exclusively) employed in the existing literature (BAU) and those that have been modified in our study.

In essence, certain basic conditions usually considered are upheld. Thus, the prices, costs and the discount rate are constant and known [27]. Although the original papers on optimal forest rotation considered one only wood product, as in other studies [34], we have considered different wood assortments. Conversely, although some authors have vindicated for mixed stands [12], only pure stands are considered here. Furthermore, in

contrast to other studies [35], neither a stochastic environment nor the presence of taxes has been incorporated into the analysis [36].

Table 1. Assumptions included in this study.

	BAU	This Study
Number of Ecosystem Services (ES)	1	>1
Deterministic scenario	Yes	Yes
Production Function	1	>1
Taxes/Subsidies	No	No
Planning horizon finishes when trees are cutting	Yes	No
All the ES are considered under infinite rotations	Yes	No
Only non-coppicing management techniques	Yes	Yes
Only monospecific plantations are considered	Yes	Yes
Only a fixed initial tree density	Yes	No
No thinning regimes	Yes	Yes
Several wood products are considered	No	Yes
Different preferential weights for each ES	No	Yes

BAU (Business as usual): initial assumptions from the literature.

The primary alterations are a consequence of the incorporation of multiple ES into the analysis, as previously explained, and the determination of the optimal stand density for each of these ES. This issue has been previously addressed in the literature [37], although typically in non-plantation forests. To the best of our knowledge, no studies have tested whether the plantation density selected for timber production is optimal for other ecosystem services in a planted forest. Furthermore, in contrast with other studies [25], the Faustmann hypothesis (infinite rotations) is not necessarily considered for all ES other than wood.

Numerous countries have established targets affecting to emissions reductions by 2050 [38,39], however we will not take this point into account in this study. Another distinction is that for certain ES, such as carbon sequestration, the planning horizon does not coincide with the initial rotation period. Moreover, the proposed models differ from the majority of the analyzed studies by allowing the decision-maker to assign different weights to each ES. An exception to this trend is a study focusing on productive forest plantations in Brazil [40].

2.3. Methodology

Based on the analysis presented, the central hypothesis of this study posits that the integration of silvicultural decisions, the assessment of different ES and the individual preferences of each decision maker regarding these services can influence the economically optimal forest rotation. Additionally, the problem can be addressed in a discrete way, allowing the inclusion in the analysis of ES services that lack a market price. Consequently, the methodology employed has been categorized into two distinct approaches. The first (Model A) conducts a conventional analysis of optimal rotation calculation, with a focus on the option of modifying the applied silviculture when a new ES is incorporated into the analysis. The second model (Model B), conversely, adopts an alternative perspective: it involves selecting the management alternative according to various objectives (ES) that can be quantified in non-monetary units.

2.3.1. Model A

This model is based on the expressions usually presented in the literature [27,41]. These expressions assume the Faustmann hypothesis and aim to maximize the land expected value (*LEV*). Equation (1) shows a generic expression, wherein each component corresponds to an ES and is suitably weighted by a preferential weight α . It was initially assumed that

the ES considered in the analysis reflected complementary uses, following the classification proposed by [42]. In Equation (1), the subscript i refers to any year within the specified planning horizon, the subscript k indicates the number of ES under consideration, and the subscript w captures the different timber assortments included in the analysis. The parameters $P_w, \dots, P_z$ indicate the market price associated with the quantity of ES in the year considered, whereas V_{ikw}, X_{ikw} represent the quantity of each ES considered (wood and carbon, respectively). All of the aforementioned elements are discounted with a rate $r_1, \dots, r_K$, depending on the ES analyzed (it may be the same for different ES). The variables $Cost_{wo}, Cost_K$ represents the costs associated with the management of each ES, except fixed costs ($FixC$), which are calculated separately when considering a joint production system. Without loss of generality, we compute this component with the same discount rate as the first ES considered in the analysis, which is wood.

$$LEV = \left[\begin{aligned} & \alpha_1 \cdot \frac{\left[\sum_{i=1}^T \sum_{k=1}^K \sum_{w=1}^W P_w \cdot V_{ikw} \cdot e^{-r_1 \cdot t} - \sum_{i=1}^T \sum_{k=1}^K \sum_{w=1}^W Cost_{wo} \cdot V_{ikw} \cdot e^{-r_1 \cdot t} \right]}{1 - e^{-r_1 \cdot t}} + \dots \\ & + \alpha_K \cdot \frac{\left[\sum_{i=1}^T \sum_{k=1}^K \sum_{w=1}^W P_z \cdot X_{ikw} \cdot e^{-r_K \cdot t} - \sum_{i=1}^T \sum_{k=1}^K \sum_{w=1}^W Cost_K \cdot X_{ikw} \cdot e^{-r_K \cdot t} \right]}{1 - e^{-r_K \cdot t}} - \\ & \sum_{i=1}^T \frac{FixC \cdot e^{-r_1 \cdot t}}{1 - e^{-r_1 \cdot t}} \end{aligned} \right] \quad (1)$$

2.3.2. Model B

In this model, multiple ES are combined, each measured in physical units, for each management alternative, employing the extended goal programming (EGP) technique [43,44]. In accordance with a methodology previously proposed [45], the analysis begins with the identification of F management alternatives, and G ES over the specified planning horizon (T). The objective is to obtain a ranking of the alternatives according to the decision-maker preferential weights and the values of each management alternative in relation to the ES previously defined.

To implement this technique, it is first necessary to obtain the normalized values of the management alternatives matrix in relation to ES (R_{fgi}). The subsequent phase entails the definition of the decision variables X_{fi} , which are binary. This means that they take the value 1 if the management alternative f is selected, whereas a value of 0 is assigned in all other cases. In Equation (2) the achievement function is shown. As in any goal programming model, the variables to be minimized are the deviation variables ($n_{gi}; p_{gi}$) defined for each goal (3) and suitably weighted by the preferential weights given to each of them. For each goal, the corresponding target must be defined $\bar{t}_g$ (4), which can be obtained in various ways [46,47]. The variable D measures the maximum deviation between the value achieved by an ES and its respective target value. As in any EGP model, Equations (2)–(5) allow, to obtain different solutions, depending on the parameter λ . For $\lambda = 1$, the solution obtained is the most efficient one, optimizing the “average” achievement. Conversely, for $\lambda = 0$, the most “balanced” solution was determined. Other intermediate values between the open interval (0,1) allowed the achievement of a compromise between the two aforementioned solutions [48]. The Equations (6)–(9) ensured that the hypothesis regarding the selection of a single management alternative over the course of the planning horizon would be fulfilled. The solution of this model allows for the identification of the most sustainable forest management alternative.

$$Min (1 - \lambda) \cdot D + \lambda \cdot \left[\sum_{g=1}^G \sum_{i=1}^T \sum_{f=1}^F \left(\alpha_{fg} \cdot n_{gi} + \beta_{fg} \cdot p_{gi} \right) \right] \quad (2)$$

$$\text{s.t.} \quad \left(\alpha_{fg} \cdot n_{gi} + \beta_{fg} \cdot p_{gi} \right) - D \leq 0 \quad n_{gi} \geq 0; \quad p_{gi} \geq 0 \quad (3)$$

$$\sum_{l=f}^F \bar{R}_{fgi} \cdot X_{fi} + n_{gi} - p_{gi} = \bar{t}_g \quad (4)$$

$$\sum_{i=1}^F X_{fi} = 1 \quad i \in \{1 \dots T\} \quad (5)$$

$$X_{fi} \in \{0, 1\} \quad (6)$$

$$\prod_{i=1}^T X_{fi} = q_i, \forall i \quad (7)$$

$$q_i \in \{0, 1\} \quad (8)$$

$$\sum_{i=1}^l q_i = 1 \quad (9)$$

2.4. Application

The case study to be developed refers to eucalyptus plantations (*Eucalyptus* spp.) in Brazil, which have demonstrated a consistent trajectory of expansion [49], accumulating 7.6 million ha in 2022 [50]. Furthermore, projections indicate that the area planted with eucalyptus is likely to increase in the coming years [51]. Even though, when focusing on pulpwood plantations, their financial performance as measured by the internal rate of return has shown a decreasing trend in recent years [52,53]. Two ES will be considered in the analysis: a provisioning ES, related to wood production (according to different timber assortments), and a regulation ES: carbon sequestration.

2.4.1. Modelling Eucalyptus Plantations

The software SisEucalyptus from Embrapa, the Brazilian Agricultural Research Corporation [54,55], which has been used in numerous studies [40,56], was employed to calculate these plantations growth. An average site index of 34 was selected, and the software provides the required data for estimating annual stand growth, carbon sequestration, and the wood products obtained in each timber harvest for different spacings. As other authors have done [57], the wood assortment is composed by: energy, pulpwood and two classes of sawtimber. Simulations were conducted for rotations ranging from 4 to 25 years (the length of the planning horizon), and with spacing levels varying from 500 to 2500 trees/ha, resulting in 11 cases. Although the software allows for this possibility, for simplicity, different silvicultural scenarios (i.e., thinnings) for each spacing were not included. As well as the potential for increased timber production over successive rotations, both in terms of genetic improvement and silvicultural practices [58]. Also, in contrast with other studies [59], the possibility of incorporating coppicing into the analysis was not explored, the reason why only one production function is used in the analysis. A discount rate of 8% has been applied. Costs and price data are included in Appendix A; costs refer to a typical scenario for this species (3 × 3 m) which has been used to calculate imputed costs for each spacing.

2.4.2. Carbon Hypotheses Considered

First, it should be noted that in all cases the starting point is a bare land. This means that the case of carbon credits is reduced to afforestation on non-forested land. We also make the assumptions of additionality and permanence [60]. As discussed above, instead of assuming potential revenues from this ES in perpetuity, it has been assumed that these revenues end in 25 years (year 2050). Although there are alternative methods for calculating

carbon sequestration [61], we assume, as in many studies [7], that each year the net carbon capture is computed as the annual stand growth increment minus the carbon emissions occurring in that year.

Regarding the economic aspects, although Model A allows the inclusion of different discount rates for each ES, as proposed in some papers [27], we used timber's discount rate for both ES, since it is similar to a private optimum [10]. Unlike studies in some countries that follow current national regulations [62,63], the lack of a similar system in Brazil forced us to seek information in voluntary carbon markets. Thus, data on the carbon price per ton (see Appendix A) were obtained from a marketplace [64] by selecting ARR (afforestation, reforestation, revegetation) type projects in the area. Transaction costs were obtained from VCS (Verified Carbon Standard) development costs data [65].

Another key decision would be what assumptions are made regarding the re-emission of the carbon contained in the wood resulting from the timber harvest. The most common one, especially at the national level, would be instantaneous oxidation [66]. In other words, it is assumed that when the stand is harvested all the carbon is re-emitted to the atmosphere. Although there are several publications [67,68] justifying different half-life values for primary wood products, it has been considered appropriate to follow the IPCC recommendations [69], for both the lifetime of wood products and the degree of carbon re-emission until they reach some preset dates. In short, this means that the carbon captured in a rotation is re-emitted over a period longer than this rotation, but only calculated over the planning horizon considered in the analysis.

2.4.3. Models (A) and (B)

Equations (1) and (2) above have been modified for this case study. Model (A) includes the revenues and costs of timber and carbon sequestration and assumes the same discount rate and equal preferential weights for each of the criteria. In this model the planning horizon is 25 years, and the term $Cost_K$ includes the re-emission of carbon over the planning horizon. On the other hand, it is also necessary to include the fixed costs of carrying out this type of project.

Model B has been outlined considering the two criteria mentioned above: the first is related to monetary income (in euros), and is linked to the private optimum, while the second is linked to an environmental optimum and aims to optimize the carbon balance (tCO_2) over the given planning horizon. The targets for each goal have been set as the ideal values for each ES. As in Model (A), the preferential weights for each ES were initially assumed to be identical.

3. Results

Table 2 shows the results obtained by applying Model A for site index 34.

It can be seen how the Faustmann rotation varies between 8 and 10 years for each spacing. However, the optimal solution would be to choose a spacing of 500 trees per ha, since this would give a higher *LEV*, as can be seen in the third column. This column also shows how, as the number of trees per ha increases, there is a reduction in *LEV*.

Additionally, it is useful to complement these results with the information shown in Table 2. Columns 4 and 5 show the results assuming carbon is not considered (i.e., the carbon price is zero). The results for rotation length are very similar. On the other hand, when observing the reduction of *LEV*, it becomes evident that the importance of carbon capture rises as the number of trees per hectare increases.

Table 2. Results from Model A.

	O.R.	LEV	O.R. No C	LEV No C	C	C	MSY
Trees/ha	Years	€/ha	Years	€/ha	CO ₂ Tons	Years	Years
500	9	17,788.3	9	14,628.5	898.58	14	9
600	9	17,703.1	9	14,585.4	898.15	13	9
700	9	16,138.2	9	12,996.4	903.87	13	9
800	10	15,610.6	10	12,439.9	907.88	13	8
1000	9	14,804.0	9	11,621.0	915.84	15	8
1200	9	14,004.7	8	10,852.5	916.85	15	8
1400	9	12,586.7	8	9495.1	903.40	14	8
1600	8	11,649.8	8	8599.9	883.47	14	7
1800	8	10,591.9	8	7578.3	859.87	14	7
2000	8	9433.6	8	6467.2	834.31	14	7
2500	8	6268.6	8	3448.9	768.81	14	7

All calculations were done for site index 34. O.R.: optimal rotation; LEV: Land Expected Value; C: carbon; MSY: Maximum sustained yield. Carbon has been calculated as a balance: sequestration minus emissions.

According to Table 2, there exists a discrepancy between the maximum carbon sequestration potential and the corresponding optimal rotation age (as indicated in columns 6 and 7) when compared to the results of Model A (as shown in columns 2 and 3). It is evident that prioritizing carbon optimization results in extended rotations and a notable reduction in profitability. Finally, the last column shows what would be, for each spacing, the optimal rotation, according to the maximizing sustainable yield criterium.

It is very easy to modify the initial assumptions and to perform several sensitivity analyses according to changes in the initial values. Considering only the most illustrative scenarios, Table 3a shows the findings for a scenario where there is no carbon, and does not differentiate between wood products (all timber goes to pulpwood). In this scenario, the optimal rotation remains unchanged at 8 years, with only minor variations in LEV observed across spacings of 500 to 1200 trees per hectare. In contrast, Table 3b shows the above analysis for a worse site index (SI = 24), where a marked decrease in profitability is evident. Here, a spacing of 500 trees per hectare emerges as the most beneficial option. Notably, the optimal rotation age extends to 12 years, and the role of income from carbon capture becomes increasingly significant in this context.

Table 3. Results for other scenarios. (a) Results without carbon and with one wood assortment (pulpwood)—Site index = 34. (b) Results for Site Index = 24.

(a)		
Trees/ha	O.R. Years	LEV €/ha
500	8	5153.4
600	8	5110.3
700	8	5428.8
800	8	5465.3
1000	8	5598.2
1200	8	5552.4
1400	8	4788.8
1600	8	4411.8
1800	8	3855.3
2000	8	3164.9
2500	8	1011.5

Table 3. Cont.

(b)							
Trees/ha	O.R. Years	LEV €/ha	O.R. No C Years	LEV No C €/ha	C CO ₂ Tons	C Years	MSY Years
500	12	3263.5	13	1952.6	371.95	13	13
600	12	2381.5	13	1236.1	373.17	25	11
700	12	1947.6	13	791.8	379.90	25	11
800	12	1616.0	13	465.2	389.31	25	11
1000	12	1073.5	13	−122.8	402.58	25	10
1200	12	562.9	13	−691.5	408.79	25	10
1400	12	−9.7	13	−1310.8	411.82	25	9
1600	12	−597.8	13	−1942.3	408.53	25	9
1800	11	−1267.7	13	−2664.4	400.96	25	9
2000	12	−1968.4	13	−3363.3	391.26	25	9
2500	12	−3856.0	13	−5306.2	367.99	13	8

O.R.: optimal rotation; LEV: Land Expected Value; LEV no C: LEV without carbon; C: carbon; MSY: Maximum sustained yield.

Regarding Model B, Table 4 shows the results for the two solutions considered $\lambda = 0$, and $\lambda = 1$). Note that since this is a ranking, only the solutions for the best 20 alternatives are included, where each alternative is a combination of spacing and rotation.

Table 4. Solutions Model B.

$\lambda = 1$					$\lambda = 0$			
Ranking	Spac. Trees/ha	Rotation Years	NPV €/ha	Carbon tCO ₂	Spac. Trees/ha	Rotation Years	NPV €/ha	Carbon tCO ₂
1	500	13	16,217.5	894.7	500	13	16,217.5	894.7
2	500	9	17,788.3	845.2	600	13	15,967.9	898.2
3	600	13	15,967.9	898.2	500	9	17,788.3	845.2
4	500	10	17,710.8	831.5	500	12	16,628.0	843.7
5	500	11	15,295.0	898.6	500	11	15,295.0	898.6
6	600	9	17,703.1	825.7	600	11	15,270.7	893.2
7	600	14	15,270.7	893.2	700	12	15,230.6	843.4
8	700	13	14,747.9	903.9	600	9	16,472.6	837.3
9	500	12	16,628.0	843.7	500	10	17,710.8	831.5
10	800	13	14,213.5	907.9	700	13	14,747.9	903.9
11	600	12	16,472.6	837.3	600	9	17,703.1	825.7
12	600	10	17,615.2	795.5	700	9	16,138.2	823.5
13	500	11	17,706.7	787.0	800	12	14,656.5	842.7
14	500	15	14,351.3	887.4	500	7	16,375.7	817.1
15	700	14	13,934.9	893.0	800	9	15,590.8	816.2
16	1000	13	13,331.3	909.3	500	15	14,351.3	887.4
17	500	7	16,375.7	817.1	600	15	14,318.8	877.4
18	700	9	16,138.2	823.5	800	13	14,213.5	907.9
19	600	15	14,318.8	877.4	1000	9	14,804.0	805.9
20	500	8	17,432.8	783.4	700	14	13,934.9	893.0

spac.: spacing; NPV: Net Present Value.

A sensitivity analysis (Model B) has been carried out in relation to the preferential weights used. In the absence of a survey or similar, we simply parameterized two scenarios. In the first, the economic ES has been weighted twice as much as the carbon ES. In the second scenario, carbon has a weight that is double that of the economic objective. The results are shown in Table 5, and for the most balanced solution ($\lambda = 0$), there are no

variations in the ranking. On the other hand, for $\lambda = 1$, the solutions in the top five positions undergo significant changes. Thus, it can be seen how the optimal rotation for these solutions is lengthened compared to the previous scenario. In any case, since the range of carbon variation (ideal minus anti-ideal values) is not very large, a priori no major changes in the ranking were expected. If other ES were introduced into the analysis, the variability of the results would probably be greater.

Table 5. Sensitivity analysis related to preferential weights.

Ranking $2 \times n1 + 1 \times n2$				
$\lambda = 1$			$\lambda = 0$	
Ranking	Spacing Trees/ha	Rotation Years	Spacing Trees/ha	Rotation Years
1	500	9	500	13
2	500	10	600	13
3	600	9	500	9
4	500	13	500	12
5	600	13	500	11
Ranking $1 \times n1 + 2 \times n2$				
$\lambda = 1$			$\lambda = 0$	
Ranking	Spacing Trees/ha	Rotation Years	Spacing Trees/ha	Rotation Years
1	500	13	500	13
2	600	13	600	13
3	500	11	500	9
4	700	13	500	12
5	600	14	500	11

$n1, n2$: preferential weights assigned to each ES.

4. Discussion

We have developed two models to integrate different ES in forest plantations. The first one (Model A) is based on the idea that it is possible to monetize the any ES in general. Applying it to the case study, where wood production and carbon were considered as ES, it is shown, comparing Tables 2 and 3a, that the profitability of including different process per timber assortments increases significantly, causing a slight increase in rotation length, especially at reduced trees-per-hectare. The least dense spacing analyzed (500 trees/ha) is where the optimum occurs, according to the hypotheses proposed.

Regarding Model B, which integrates carbon as an additional ecosystem service beyond wood without requiring monetary calculations in an EGP model, the results reveal different optimal combinations of rotations and spacing, depending on the chosen solution type. The best five solutions range between 500 and 600 trees/ha, which are significantly lower than the spacing commonly used in Brazilian plantations. The optimal rotation varies from 9 to 13 years for these best solutions. As suggested by some authors [70], the correct choice of spacing is crucial, especially when considering ecosystem services other than wood and when the site index is lower. According to the hypotheses of this study, the combination of optimal spacing and the introduction of carbon in the analysis leads to viable solutions with a slightly shorter rotation (Table 3).

Unlike other related work [33], where the inclusion of carbon causes a rotation lengthening, this situation is not observed with the results obtained according to Model A. Moreover, even for some spacings, the rotations obtained are longer than the maximum sustained timber yield rotation. It has also been shown that considering several timber

assortments instead of one slightly lengthens the rotation. This hypothesis of rotation lengthening when considering a joint production with other ES is indeed verified by observing the results of Model (B). Moreover, for both models the reduced trees-per-hectare gives better results than the spacings usually used in the case study (around 1000 trees/ha). Besides, contrary to other papers [6,71], there were not many solutions where the rotation tends to infinity (no timber harvest). Only for the lower site index considered and spacings between 600 and 2500 trees/ha the optimal rotation recommended in this case by optimizing the carbon balance is 25 years (see Table 3b).

These models could be extended with the introduction of other ES. A clear candidate in the analyzed case study would be the provisioning ES related to water, since there are studies that recommend a balance between timber production and water [72]. An example of a study of the optimal rotation with wood, carbon and water in other forest systems can be found in [71]. In other plantations, it has been shown that water can be considered in the same way as carbon in Model (B): by introducing a payment for increased water availability or by incentivizing silvicultural activities as in [73]. On the other hand, other studies show that Brazilian landowners are willing to change their silvicultural practices in eucalyptus plantations, although they prefer to reduce rotation rather than change spacing [74]. However, the latter variable is very easily related to water availability because of the lower consumption throughout the rotation at low plantation densities [75].

The results obtained in this study can be very useful to feed a Decision Support System [76,77], that helps owners to optimize their forest plantations according to their preferences, the ES considered and the optimal silvicultural treatments in each case. Moreover, it could even include a group-decision making module to integrate the preferences of different stakeholders, hybridizing with the previous models [78]. Furthermore, it can be complemented with extensions that include options such as coppice rotation, which, according to some authors, accounts for 20%–30% of these plantations in Brazil [75], or the possibility of modifying the volume and the wood products obtained after the first rotation.

The study's limitations can be delineated into three main components. The first component concerns the specific attributes of the plantations and the silvicultural methods examined in the case study. Thus, we did not consider the alternative of mixed-species forest stands. Although integrating diverse species could enhance various ecosystem services, the lack of suitable production models deterred us from exploring this scenario. Diversifying species is justified for several reasons: environmentally, it increases biodiversity [79], and productively, it introduces nitrogen-fixing trees, reducing the need for future fertilization [80]. Also, different possibilities of integrating agroforestry systems could be considered [81]. Besides, silvicultural practices are only used in this study to change stand spacing. Incorporating scenarios that combine thinning hypotheses with different spacings and coppice systems would be useful to the manager [82,83], although the number of potential alternatives would increase exponentially. The second set of limitations pertains to aspects associated with uncertainty. Although the planning horizon is significantly shorter than for other species and forest systems, it would also be useful to apply the models presented in this study under different climate change scenarios [84]. We have shown different extensions that can be applied in this study, but the option of developing non-deterministic scenarios that solve the problem assuming changes in the different parameters and variables considered in the previous models should not be forgotten. An example of this could be the use of Monte-Carlo techniques [85]. Finally, the last limitation pertains to spatial considerations. Thus, it should be kept in mind that the stand-level rotation concept may be subject to meet requirements at the spatial level, which include an acceptable mosaic of both plantations and native stands, in order to improve the performance of different ES [86].

5. Conclusions and Management Implications

5.1. Conclusions

Despite the large amount of literature published on the subject, there are not many studies that allow to modify stand conditions affecting more than one ES in order to define the economically optimal forest rotation. In other words, the optimal silviculture applied so far has been the one most suitable for timber production, and the other ES were subordinated to it. This paper has proposed a methodology to address this problem that includes two models, one that allows to decide which is the optimal rotation and silviculture according to different ES when these are measured in monetary units. The second one extends this vision considering the ES in their psychical units and allows calculating the optimal rotation through a discrete model solved through multi-criteria techniques. In this study, the methodologies were applied to the scenario of eucalyptus plantations in Brazil, resulting in the confirmation of the general hypothesis proposed in the research. Thus, the optimal rotation occurs with much less trees per hectare than usual when carbon and timber are integrated (with four different timber assortments). Profitability also increases significantly, despite the fact that carbon credit revenues are not considered perpetual due to climate agreements in different countries. On the other hand, these models make it possible to include in the analysis different preferential weights with respect to the different ES, leading to potentially different solutions that are closer to the preferences of the different stakeholders interested.

5.2. Management Implications

The findings of this study have several implications for the effective management of certain forest plantations. For instance, the optimal rotation determined solely based on timber production and the applied silvicultural management can be readily adjusted when additional ES are taken into account. In other words, it should not be presumed that a joint production system will yield the same optimal solution as when a single management objective is prioritized. Therefore, it is advisable to incorporate information on ES beyond timber in the analysis whenever feasible. This approach will facilitate forest management planning that aligns more closely with the inherent multifunctionality of forest systems, allowing managers to consider the preferences of various stakeholders regarding the ES in question.

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Abbreviations

The following abbreviations are used in this manuscript:

ES	Ecosystem Services
GHG	Greenhouse Gases
BAU	Business as Usual
LEV	Land Expected Value

Appendix A

Table A1. Price and costs data used in this study.

Item	Cost	Source
Price (€/m ³)		
energy	30.3	a
pulpwood	13.0	a
sawnwood I	50.0	b
sawnwood II	70.0	b
carbon	10.0	c
Establishment cost (€/ha)		
planting	1005.8	a
forest practices year 1	2083.4	a
forest practices year 2	1083.4	a
Annual cost (€/ha) × year	80.5	a
Carbon certification cost (€/ha)	256.0	d
annual carbon cost (€/ha)	16.9	d

a: Personal communication from Joao Carlos Teixeira Mendes (USP); b: CEPEA: <https://www.cepea.esalq.usp.br/upload/revista/pdf/0728482001708536797.pdf> (accessed on 16 April 2024); c: various marketplace; d: VERRA.

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