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Determining the optimal harvest cycle for copaíba (*Copaifera* spp.) oleoresin production

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ABSTRACT

Copaíba oleoresin is a medicinal product obtained from several species of Copaifera trees (*Copaifera* spp.), and it is used for its healing and anti-inflammatory properties. Oleoresin is extracted via holes drilled into the trunks of copaíba trees, which are then plugged and periodically harvested in repeated cycles. To date, the optimal harvesting cycle and the factors that influence oleoresin production are unknown. Therefore, the main objective of this study was to analyze various harvesting schedules to determine the optimal cycle in an attempt to obtain maximum oleoresin production or the maximum net present value associated with production. The study took place in Paragominas, Pará (Brazil), and based on the resulting data, a set of alternatives for 1- to 5-year cycles with a planning horizon of 10 years was created. The data were analyzed within two different contexts: a deterministic one and another scenario that assumed that certain variables exhibit non-deterministic behavior for which a Monte Carlo simulation was used. Based on the available data, three scenarios were proposed that differed according to the hypotheses employed to estimate production for years when no measurements are available. The results show that, regardless of the various contexts and scenarios, the optimal harvesting cycle for copaíba oleoresin is three years, which is consistent with some previously published recommendations. Finally, the opportunity cost of not choosing the optimal cycle does not seem to be very high.

1. Introduction

Tree exudates—gums, resins and oils—as well as bark, roots and tubers account for a large proportion of commercial non-timber forest products (NTFPs) obtained from natural environments (Ticktin, 2004). Among the products extracted from oils and resins, one of significant local importance in the Amazon basin is the production of copaíba (*Copaifera* spp.) oleoresin (Newton et al., 2012a), a non-perishable product with a high unit price (Newton et al., 2011). It is used for various purposes, most notably in the pharmaceutical industry for its anti-inflammatory and anti-bacterial properties and in the cosmetics industry in the manufacture of soaps, shampoos and lotions. Furthermore, according to official statistics (IBGE, 2011), approximately 2.13 million people are estimated to belong to either traditional or other communities located in the forest area of the state of Pará where member individuals extract this product. These populations use these NTFPs for both subsistence (self-consumption) and as a means of obtaining money or other products through exchange (Belcher and Schreckenberg, 2007). Ultimately, these products complement the growth and development of traditional communities and disadvantaged families (Pattanayak and Sills, 2001; Belcher and Schreckenberg, 2007). Finally, official statistics in Brazil recorded the production of 580 t of copaíba oil in 2010, which fell to 214 t in 2011 (IBGE, 2011), that mainly occurred in the states of Amazonas (78.87%), Pará (15.02%) and Rondônia (5.63%).

It is frequently assumed that certain Amazonian non-timber forest products could be managed in a manner more compatible with timber production (Duchelle et al., 2012; Shanley et al., 2012). This study does not address this topic as the joint production of copaíba oleoresin and timber is not contemplated. We only consider the production of copaíba oleoresin in isolation, excluding it from the analysis of potential revenues associated with copaíba timber. In fact, in some states in the Amazon, the law prohibits the harvest of copaíba trees (Kluppel et al., 2010). To date, there are no biometric models for the estimation of an optimal rotation when considering the combined production of both oleoresin and timber. In contrast to other Amazonian non-timber forest products, such as *Carapa guianensis* Aubl. (Klimas et al., 2012), the age at which copaíba oleoresin production is maximized remains unknown, and there is no model of its oil production throughout

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the life of an individual tree. This production problem has also not yet been addressed from a spatial perspective (Albers and Robinson, 2013) as no information on the decision-making of collectors is available. This particular limitation is an issue of concern for the species because the density of individuals is usually very low. For example, Herrero-Jáuregui et al. (2012) reported densities of between 0.11 and 0.21 trees over 45 cm dbh (diameter at breast height) per ha, whereas Schulze et al. (2008) inventoried areas with a slightly higher density. Finally, Newton et al. (2012a) reported densities of between 0.01 and 1.69 trees per ha with dbh ranging from 10 to 45 cm.

Although it used to be common practice to cut down copaíba trees to extract their oleoresin, in recent years it has been established that copaíba oleoresin can be extracted directly from living trees of these species (*Copaifera* spp.) via holes drilled into the trunk or by uncovering previously drilled holes plugged with a piece of wood. This collection technique can be repeated periodically in defined harvesting cycles although it should be noted that not all drilled trees produce oleoresin in the first few harvests. Ultimately, the factors exerting a major influence on oleoresin production are not yet known with any certainty (Plowden, 2003; Rigamonte-Azevedo et al., 2006; Medeiros and Vieira, 2008; Newton et al., 2011; Martins et al., 2012). The definition of a standard production cycle would be a crucial element in copaíba management because the cycle must meet two basic criteria: avoiding harm to the plant and providing the highest gain in terms of oil productivity. Currently, some recommendations based on empirical data suggest following three-year harvesting cycles (Leite et al., 2001).

According to Peters (1996), copaíba handling could be held up as a model of sustainable forest management as no alteration occurs in the forest canopy, no specimens are cut down, and no seeds are removed provided that best practices are followed. Moreover, this species is difficult to domesticate (Plowden, 2001; Homma, 2012). Harvesting is usually carried out by members of indigenous groups and traditional farming communities that live in or near the forest. However, copaíba oleoresin production for commercial purposes is a relatively recent practice, which explains the fact that the available scientific and technical studies relating to the complete production process tend to be in their early stages and are mainly concerned with sustainable management. Furthermore, no mechanisms for adding value to this product in the market have been optimized, which has limited the possibility of a more lucrative income for collectors (Santos and Guerra, 2010).

Copaíba trees have attracted increasing interest from researchers working in diverse areas. Studies have analyzed aspects of population distribution, density and structure, the differences between species and their environmental requirements (Alencar, 1982; Ramirez and Arroyo, 1990; Plowden, 2004; Rigamonte-Azevedo et al., 2006; Medeiros and Vieira, 2008; Herrero-Jáuregui et al., 2012; Martins et al., 2012; Newton et al., 2012a, 2012b), and the diameter of the trees where production is higher (Plowden, 2003). From an economic perspective, Newton et al. (2012a) estimated the number of productive trees and their oleoresin extraction value in two reserves, providing data on the prices of this product in different links of the supply chain and recommending a gradual increase of its price level. Finally, there are numerous studies analyzing the chemical characteristics of oleoresin (Lima et al., 2006; Santos et al., 2008).

Regarding the production of this NTFP, some authors estimate an average production ranging between 2.5 and 20 l of oleoresin per tree (Newton et al., 2011; Martins et al., 2012). The interval between two consecutive harvests varies depending on the study, but it is usually between 6 months and 5 years (Leite et al., 2001; Plowden, 2003; Martins et al., 2012). A key, early study was undertaken by Alencar (1982) who performed five extractions within an interval of less than two years. However, there has yet to be a conclusive study to determine the proper waiting period between two consecutive harvests (Martins et al., 2012). Also unknown is how much oleoresin can be removed without causing damage to the wider ecological and physiological processes surrounding this species, which management factors influence production, (Plowden, 2003, 2004; Medeiros and Vieira, 2008) and the level that can be extracted sustainably. Some researchers (Herrero-Jáuregui et al., 2011) argue that the extraction of copaíba oleoresin does not affect the regeneration of the species.

Taking this context into account, the main objective of this study was to estimate the optimal cycle that should be adopted for oleoresin extraction, considering both the maximum production in physical units as well as the highest associated monetary returns. In addition to oleoresin production data, certain economic variables (such as copaíba oleoresin prices) are included in our analysis. Including a case study in which repeated measurements were taken, five collection cycles were compared in which harvests were conducted at different intervals, and deterministic (certain) and non-deterministic (uncertain or stochastic) contexts were considered.

The first question that we wished to answer was whether the optimal cycle was the same for either maximizing the amount of oleoresin extracted or maximizing the net present value from production. According to some authors, the latter strategy is the optimal policy for any type of natural resource (Romero, 2012). The hypothesis tested was that there would be no difference between the two methods as production levels mostly diminish over the 10-year planning horizon, but there are no studies to date corroborating this potential coincidence of both optimal solutions. The second issue was whether the results for the optimal cycle length were the same if considering a certain context or if risk or uncertainty were incorporated into some of the model variables, such as oleoresin price. If so, the hypothesis would be that there is no evidence to assume an *a priori* outcome for possible variations in the optimal cycle.

2. Methods

2.1. Species and case study

The genus *Copaifera* belongs to the Fabaceae family and is represented in Brazil by 16 species (Veiga and Pinto, 2002). The genus is well documented in the Amazon region, and the wider *Copaifera* distribution ranges from the drier Cerrado region to dense and mixed tropical rain forest, indicating a certain plasticity in relation to habitat (Veiga and Pinto, 2002; Carvalho, 2003). In the study area, two species were found: *Copaifera reticulata* Ducke and *Copaifera duckei* Dwyer.

The study was conducted at the "Roberto Bauch" Center for Forest Management located in the "Fazenda Cauaxi", which belongs to the Tropical Forest Institute (IFT, "Instituto Floresta Tropical"). The center is located in the municipality of Paragominas in the state of Pará, Brazil (Fig. 1). The climate is humid and mesothermal with an average annual temperature of 25 °C (Alvares et al., 2013), so the forest is classified as an upland, dense tropical rain forest (IBGE, 1988) with a local average rainfall of 2200 mm that is mainly concentrated between January and June (80%). The local terrain is moderately hilly, and the predominant soil type is yellow latosol (RADAMBRASIL, 1983). The study area covers 3000 ha; there are 53 management units (MU), in which timber harvest scheduling is carried out annually, and each MU has an area ranging from 40 to 100 ha. For each defined cycle, a total of 11 MUs are randomly selected, and the effective study area covers 929 ha. In these MUs, which were kept separate to avoid mistakenly re-measuring a tree, the trees with dbh of over 35 cm were measured, and their

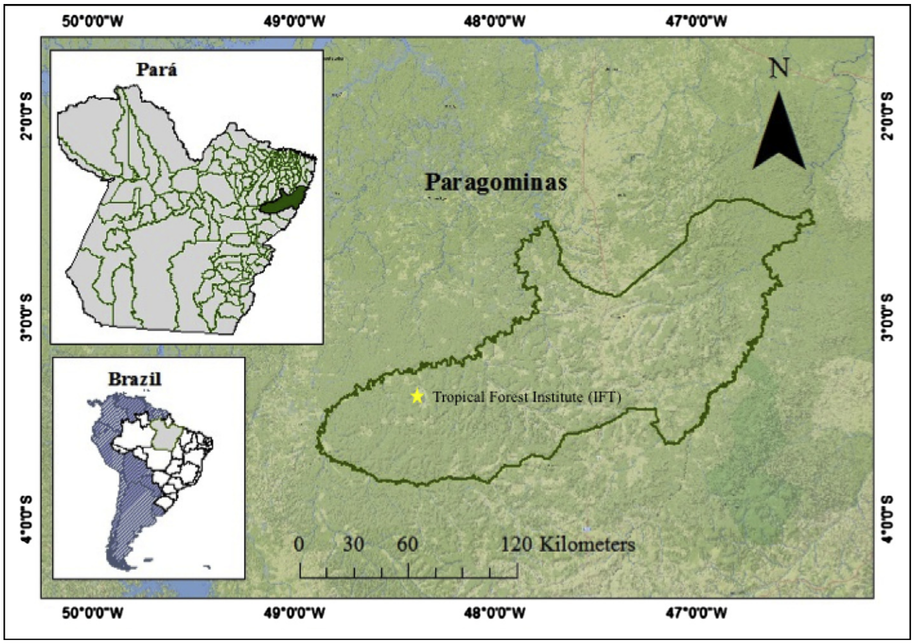


Fig. 1. Location of the forest area of the Instituto Floresta Tropical (IFT, Tropical Forest Institute) in Pará, Brazil.

oleoresin was extracted. The density of copaíba stands was calculated based on a tree census conducted every year until 2013. This census was conducted in work units (WU) that were established in the study area, and all of the trees with diameters over 35 cm dbh were measured. In other studies, the minimum diameter for extraction activities in copaíba trees was 30 cm (Leite et al., 2001; Plowden, 2003), which is similar to the 35 cm minimum adopted in our study. Finally, in contrast to certain other studies (Newton et al. 2012b), the study site is not subject to periodic flooding.

2.2. Economic variables

To calculate the net present value (NPV), a discount rate of 8% was used, a choice based on the literature related to this type of ecosystem in Brazil (Diaz-Balteiro and Rodriguez, 2006). However, as the value chain of the product is not known with any accuracy, there was no reliable information on the value of a standing copaíba tree. The average price per liter of copaíba oleoresin was therefore obtained from weekly information available in a database constructed by the Institute of Man and the Environment in the Amazon (Imazon, "Instituto do Homem e Meio Ambiente da Amazônia") for 2009–2013. Following the instructions of researchers at Imazon, the mode value for each sale of copaíba oleoresin was recorded on a weekly basis for the city of Breves, which was considered to be the site closest to the study area. The prices were standardized as a function of the inflation observed over the years, and an average price per liter of R$ 33.09 was obtained. In completing the calculation, no cost was assumed to be associated with oleoresin extraction.

2.3. Study framework

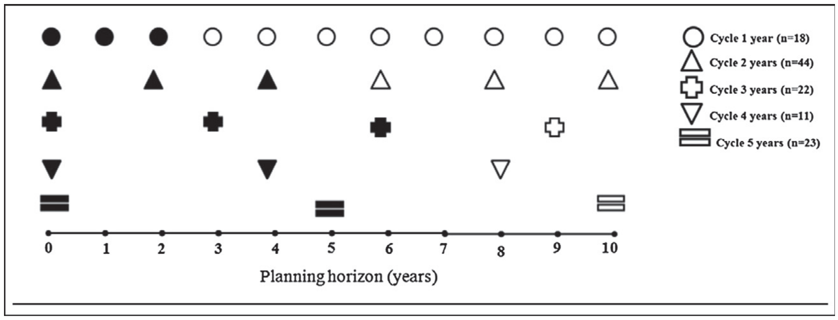
The main factors included in this study are identified below as are the main hypotheses that were considered. First, as discussed above, this study only considered the production of copaíba oleoresin and not that of other products from the tree, such as timber. Although two species are present in the study area, the results were not differentiated at the species level, which is in contrast to other studies (Newton et al., 2011; Martins et al., 2012). There are several reasons behind this decision; a distinction between the species was not made in some measurements, but when it was, the results were quite similar. In addition, the intermediaries who buy the oleoresin from forest communities do not differentiate between species, so oleoresin sold on the open market typically belongs to both species, which prevents the assignment of different prices. As a result, we were not able to assign a variable related to species for each measurement because the oleoresin was mixed from the two species.

Starting with a planning horizon of 10 years and based on the available data, five possible alternatives were identified that correspond to harvest cycles ranging between 1 and 5 years, as shown in Fig. 2. It was assumed that production is not necessarily greater in the first harvest, i.e., independent of the harvest cycle, the amount of copaíba oleoresin extracted at the initial stage is not greater than that from a subsequent extraction. Some studies support this assumption (Plowden, 2003; Medeiros and Vieira, 2008).

Furthermore, as the influence of different harvesting cycles on the quantity of oleoresin produced is not known, this study has elaborated simple hypotheses for the estimation of copaíba oleoresin production throughout the length of the entire 10-year planning horizon. This was necessary because the previous literature does not contain any studies that enable the validation of these production hypotheses. We defined three specific scenarios. In the first scenario, it was assumed that the number of copaíba trees producing oleoresin was kept constant, but the amount of oleoresin produced by each tree decreased according to the latest data available for each cycle. In the second scenario, by contrast, it was assumed that oleoresin production in each cycle was constant but that the number of trees in production decreased also according to the latest data available for each cycle. The third scenario includes a reduction in both the number of productive trees and the level of oleoresin production following the same pattern as the previous two scenarios.

2.4. Optimal cycle analysis

Once the particular cycle had been defined, copaiba oleoresin production was calculated in two ways. First, the physical production level (milliliters of oleoresin) over 10 years was calculated for



Note: "n" is the number of trees. Solid symbols were informed by field data; clear symbols were not.

Fig. 2. Copaíba oleoresin (*Copaifera* spp.) harvests based on different production cycles (1–5 years) and a planning horizon of 10 years.

each of the five cycles defined in Fig. 2. Because not all of the trees produce oleoresin when drilled, the probability that a drilled tree would produce oleoresin was calculated for each harvest in each cycle. This probability was based on our measurements considering two states: whether a tree produced oleoresin or not. Therefore, the amount of oleoresin extracted only concerned the trees that produced oleoresin in the cycle under consideration as the trees that did not produce it but that could do so *a priori* were incorporated into the probability term defined above.

Another way to calculate copaíba oleoresin production is to measure production in purely monetary terms via the calculation of profitability throughout the length of the planning horizon. In this approach, the net present value (NPV) associated with the harvest of copaíba oleoresin is calculated. This value is an indicator of the net investment returns and is widely used in forestry studies. However, variations are sometimes introduced in economic assessments of non-timber forest products. The mathematical expression of the NPV is summarized by the following equation:

$$NPV = \sum_{j=1}^{j=10} ac_j \cdot p \cdot \alpha_j \cdot \exp^{(-i,j)}$$

where NPV is the net present value; j is the year corresponding to the cycle in which extraction occurs; ac_j is the amount of oleoresin obtained in the corresponding extraction year j; p is the price of oleoresin; α_j is the probability that a tree will produce oleoresin in the corresponding extraction year j, and i is the discount rate applied.

2.5. Monte Carlo simulation

The Monte Carlo method sets out to solve mathematical problems by simulating the values of particular random variables (Sobol, 1994). This method can be applied both in situations of risk (when the probability density functions for certain variables are known) and in situations of uncertainty (when those probabilities are unknown). In the latter case, the Monte Carlo method is similar to a sensitivity analysis. The procedure is conducted as follows: starting with the knowledge of the density functions of these probabilities, the method uses, as its base, a random sample of values generated with those density functions. This process continues through multiple simulations until the model converges on stable results. The end result is an average of the observations obtained in all of the simulations (10,000). An example of this method being applied to a forest management problem was published by Rodriguez and Diaz-Balteiro (2006). The variables that were considered in a non-deterministic environment were copaíba oleoresin production in the first and the second harvest and its price. The basic characteristics of these variables are shown in Table 1.

Table 1
Variables used in the Monte Carlo simulation.

	Production in the first extraction (l)	Production in the second extraction (l)	Copaíba oleoresin price (R$/l)
Mean	2.178	0.187	33.09
Median	1.100	0.050	31.08
Maximum	12.000	0.650	53.01
Minimum	0.020	0.001	20.00
Standard deviation	3.166	0.355	6.79
Observations	48[a]	24[a]	82

[a] Refers to trees that produced copaíba oleoresin source of data: copaíba oleoresin production: field data; copaíba oleoresin price: IMAZON data.

To calculate these simulations, we used the @Risk software program (Palisade Corporation, 2012).

3. Results

First, we will present the results obtained from observational field data of copaíba trees. Next, we will show the results for the different cycles and scenarios considered.

3.1. Copaíba production

Data on copaíba oleoresin extraction, covering 118 trees, were collected for seven years (2006–2013). Fig. 3 shows the level of oleoresin from successfully producing trees in the first harvest as a function of their diameter at breast height.

When focusing on the quantity of oleoresin obtained, it is important to note that the production from the first harvest was highly variable, regardless of the harvesting cycle adopted. While some trees had several successful harvests, others had not yet produced oleoresin. The density of the sampled trees in the census was 0.17 trees/ha. According to the data shown in Table 2, the average production volume of each productive tree was 2177.5, 30.1 and 25. 4 ml per tree in the first, second and third harvests, respectively (regardless of cycle), excluding non-productive trees. Table 2 contains the percentage of trees that were hollow or dead when measurements were taken and the percentage of trees that did not produce any oleoresin in successive extractions. Some trees did not do produce in the first extraction but did produce in the following one. Table 2 also shows that the number of trees that produced copaíba oleoresin was smaller in the second and third harvests than in the first. It should also be noted that average oleoresin extraction in the first harvest was several times larger than in the second and third harvests. Finally, Table 3 shows the total copaíba oleoresin produced in each cycle.

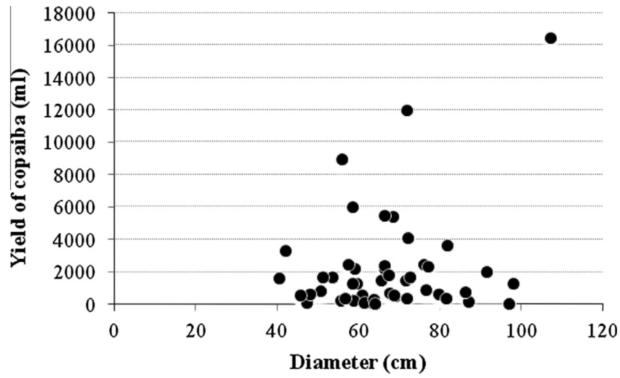


Fig. 3. Oleoresin production of productive copaíba trees in the first harvest according to the diameter at breast height (dbh) of the drilled trees in the study area.

3.2. Optimal cycle

Table 4 presents the data regarding oleoresin production and NPV for the five cycles considered and the three scenarios based on the hypothesis stated above. Included are the probability that a tree will produce oleoresin and the level of production during extraction over the entire, 10-year planning horizon for which no specific field data are available under a deterministic context. The results led to the same solution for all three forecast scenarios; the optimal cycle was three years regardless of whether production quantity per tree or the NPV per tree were maximized. The second-best cycle was one year. However, it should be noted that the differences between the three scenarios were very small, no doubt triggered by the important influence of the data from the first extraction on the results.

Table 5 presents the data considering the uncertain context according to the three scenarios and five cycles tested. Both the NPV and the average yield per tree increased slightly, but the optimal cycles were the same as in the deterministic context.

Table 4
Results for the three scenarios considered and cycles analyzed in a deterministic context[b].

Scenario	Cycle (years)	Copaíba oleoresin (l/tree) per cycle[a]	NPV (R$)
1	1	1.00	32.83
	2	0.93	30.53
	3	1.17	36.20
	4	0.90	29.92
	5	0.91	30.14
2	1	1.08	34.57
	2	0.93	30.60
	3	1.19	36.46
	4	0.90	29.92
	5	0.92	30.20
3	1	1.01	32.91
	2	0.93	30.53
	3	1.16	36.00
	4	0.90	29.92
	5	0.91	30.14

[a] Average amount produced per cycle multiplied by the probability that a tree produces oleoresin.
[b] Copaíba oleoresin data presented in this table come from our models. In the first scenario, it is assumed that the number of copaíba trees that produce oleoresin is kept constant, but a decrease in the amount of oleoresin produced by each tree occurs. In the second scenario it is assumed that the oleoresin production in each cycle is constant but that the number of trees in production decreases. The third scenario includes a reduction in the number of productive trees and in the level of oleoresin production.

Table 2
Summary of results for the different collections considered[a].

	First extraction	Second extraction	Third extraction
No of sampled trees	118	110	81
Average production where there is a harvest (ml)	2177.5	187.3	25.4
% Productive trees	41.5	22.9	30.9
% Dead trees	5.1	16.1	10.7
% Trees producing and non-producing during the previous extraction		10.1	24.0
% Trees for which production increases		0.0	9.3
% Trees for which production diminishes		18.2	5.3
% Trees for which production becomes zero		28.3	16.0
% Trees that maintain zero production		35.6	44.1
% Trees that maintain zero production since the 1st extraction			34.5

[a] Copaíba oleoresin data of this table were measured in the field.

4. Discussion and conclusions

This study attempted to define the optimal extraction cycle for copaíba oleoresin production in a case study based on 118 sampled trees. Although the optimal cycle analysis was performed at the tree level, one striking result is the low density of copaíba trees in the study area. The results of other authors (Schulze et al., 2008; Newton et al., 2012b) show higher densities than found in this study, ranging from 0.25 to 1.13 trees per hectare. Only Phillips et al. (1994) reported a similar density (0.14 trees per hectare) for trees over 45 cm dbh.

As an extraction activity compatible with other activities, such as hunting (Newton et al., 2012a), the NTFP should be considered

Table 3
Copaíba oleoresin produced in each cycle[b].

Cycle (year (s))		1			2			3			4		5	
Extraction		1°	2°	3°	1°	2°	3°	1°	2°	3°	1°	2°	1°	2°
No	No of sampled trees	18	16	15	44	44	44	22	22	22	11	11	23	17
	Productive trees	22.2	18.8	40.0	34.1	11.4	36.4	59.1	50.0	18.2	33.3	33.3	56.5	35.3
%	Non productive trees	66.7	75.0	46.7	65.9	88.6	54.5	40.9	50.0	81.8	66.7	16.7	17.4	41.2
	Dead/hollow trees	11.1	6.3	13.3	0.0	0.0	9.1	0.0	0.0	0.0	0.0	50.0	26.1	23.5
l	Total	3.41	1.00	0.60	32.86	0.64	0.35	36.2	3.36	2.15	6.94	7.30×10^{-4}	27.29	0.23
	Average[a]	0.85	0.33	0.10	2.19	0.13	0.02	2.78	0.31	0.54	1.74	1.83×10^{-4}	2.10	0.04
l/tree	Standard deviation	0.82	0.58	0.17	4.25	0.17	0.06	2.54	0.42	0.45	1.59	3.45×10^{-4}	3.12	0.08
	Maximum	2.05	1.00	0.20	16.46	0.41	0.20	9.00	1.44	1.00	3.68	7.00×10^{-4}	12.00	0.21

Note:
[a] Productive trees.
[b] Copaíba oleoresin data of this table were measured in the field.

Table 5
Results for the three scenarios considered and the analyzed cycles in a non-deterministic context[b].

Scenario	Cycle (years)	Copaíba oleoresin (l/tree) per cycle[a]	NPV (R$)
1	1	1.08	35.03
	2	1.03	33.61
	3	1.23	37.91
	4	1.06	34.13
	5	1.05	33.76
2	1	1.16	36.77
	2	1.04	33.69
	3	1.25	38.22
	4	1.06	34.13
	5	1.05	33.82
3	1	1.08	35.11
	2	1.03	33.61
	3	1.22	37.71
	4	1.06	34.13
	5	1.05	33.77

[a] Average amount produced per cycle multiplied by the probability that a tree produces oleoresin.
[b] Copaíba oleoresin data presented in this table come from our models. In the first scenario, it is assumed that the number of copaíba trees that produce oleoresin is kept constant, but a decrease in the amount of oleoresin produced by each tree occurs. In the second scenario it is assumed that the oleoresin production in each cycle is constant but that the number of trees in production decreases. The third scenario includes a reduction in the number of productive trees and in the level of oleoresin production.

to be a potential source of additional income for local communities despite knowing that not all trees drilled for the first time produce a significant amount of oleoresin. The probability that a previously undrilled copaíba tree with a diameter of 25 cm will produce oleoresin varies between 40% and 63% (Medeiros and Vieira, 2008; Newton et al., 2011). In our case, this finding was confirmed given that 41.5% of trees produced oleoresin in the first harvest. Furthermore, the variability of the production in the first harvest was very high (Table 1), which corroborates the findings of other studies (Newton et al., 2011; Newton et al., 2012a). However, it must be remembered that, in the other studies mentioned above, both oleoresin-producing and non-producing trees were mixed when calculating basic statistics, which was not the case here.

The literature also supports the hypothesis that the highest production occurs during the first harvest (Medeiros and Vieira, 2008; Newton et al., 2012a), which, again, was confirmed by our study (Table 2) without considering the cycle adopted for each harvest. The only exception to this was found by Alencar (1982) who reported higher volumes of oleoresin in the second harvest than in the first one. In short, it appears to have been established that production decreases in the second collection if the trees only produced copaíba oleoresin once (Plowden, 2003; Medeiros and Vieira, 2008). Moreover, this decrease can be quite abrupt as it was with Newton et al. (2012a).

One notable feature of the data is the great importance of the initial harvest for estimating optimal production cycles. In fact, between 84% and 94% of the total amount produced in the various cycles was provided by the initial harvest. This pattern implies that different harvests from the same tree will produce returns well below that of the first harvest and will usually continue to diminish (Martins et al., 2012).

Hollow and rotting copaíba trees are common both before and after extractions, although there are unresolved aspects regarding the reasons behind their formation (Plowden, 2003). This study highlighted the existence of a number of trees, although not a large one, that are no longer productive and of some trees that have not produced since their first harvest. The proportions are of a similar order of magnitude to those from other studies (Medeiros and Vieira, 2008).

An immediate conclusion reached from this study is that the optimal cycle for copaíba oleoresin extraction changes little whether production is measured based on NPV or calculated throughout the cycle. This result has been explained by the importance of the data associated with the first extraction (always more than 77% of the total value for either NPV or oleoresin production) regardless of the scenario considered. This implies that variations in parameters, such as the discount rate, do not have a significant influence on the optimal cycle. However, if the starting point were previously drilled trees, the conclusion regarding the optimal cycle is likely to be different. In order to combine other possibilities for defining the optimal cycle, one option would be to allow alternatives with different cycles during the planning horizon using dynamic programming (Diaz-Balteiro and Rodriguez, 2006). However, that possibility was discarded due to data deficiencies in relation to all of the possible combinations that could occur between different cycles over 10 years. Finally, the results obtained in this study can be considered preliminary to some extent given that we did not have field data for all of the oleoresin harvests from the five different cycles for the duration of the planning horizon. This was because the harvesting cycle for an individual tree was between one and five years, i.e., it did not last for the entire 10-year planning horizon, so simulations were used to fill the gap.

Moreover, for both of these criteria, the most appropriate cycle is three years. This three-year figure has already been given by empirical studies (Leite et al., 2001 and Pinto et al., 2010), although Newton et al. (2011) disagree with this minimum interval between successive extractions. Some papers do suggest longer cycles (e.g., 8 years in Herrero-Jáuregui et al., 2011). In summary, no consensus exists in the literature on the optimal cycle of copaíba oleoresin harvesting.

Interestingly, the results regarding the optimal cycle of copaíba oleoresin do not vary between deterministic and non-deterministic contexts. Nevertheless, the non-deterministic scenario only considers the three defined variables. In theory, were a larger dataset available, it would allow for a non-deterministic scenario for variables not considered in this study, such as the probability that a previously drilled tree would produce oleoresin.

A potential application of these results that would be of great interest in forest management would be the calculation of the opportunity cost, both in physical and monetary units, of failing to correctly choose the optimal cycle. Due to the great importance of the value of the initial harvest, this opportunity cost seems to be low. Moreover, it is important to add that, in this paper, we have not included extraction costs in the analysis. If these costs were known and were incorporated into the previous scenarios, the results would change in terms of NPV but possibly not in terms of the optimal production cycle. In this hypothetical case, however, we would have to know the variation in cost between successive harvests during the planned cycles beforehand. If this variation does not exist, i.e., the costs directly associated with the extraction of copaíba oleoresin are the same for all cycles, the optimal cycle would not change; only its profitability would be modified, and we would not need to calculate these costs. According to some authors (Guerra, 2008; Santos and Guerra, 2010), there seems to be a very slight variation in the costs (2.3%) every five years, so this assumption should not yet be discarded.

We believe that the results of this research could be useful to people in forest communities by enabling them to predict the amount of copaíba oleoresin that can be extracted. In addition, this information could help to optimize other NTFP extraction cycles because the maximization of production levels over time allows extraction to become more efficient. It should be noted, however, that we have no spatial models of the behavior of the people who extracted the copaíba oleoresin and other NTFPs in our case study, so we were unable to consider and optimize factors such as distance to markets or location decisions within the forested area. In short, we have temporally optimized the harvest cycle but have not explicitly incorporated spatial factors into the decision framework. These spatial issues and the integration of other NTFPs into these analyses represent an important future line of research.

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References

Albers, H.J., Robinson, E.J.Z., 2013. A review of the spatial economics of non-timber forest product extraction: implications for policy. Ecol. Econ. 92, 87–95.

Alencar, J., 1982. Estudos silviculturais de uma população natural de *Copaifera multijuga* Hayne – Leguminosae, na Amazônia central. 2 – produção de óleo resina. Acta Amazônica 12, 79–82.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift 22, 711–772.

Belcher, B., Schreckenberg, K., 2007. Commercialisation of non-timber forest products: a reality check. Dev. Policy Rev. 25, 355–377.

Carvalho, P.E.R., 2003. Espécies florestais brasileiras: recomendações silviculturais, potencialidades e uso de madeira. EMBRAPA-CNPF, Colombo, p. 640.

Diaz-Balteiro, L., Rodriguez, L.C.E., 2006. Optimal rotations on *Eucalyptus* plantations including carbon sequestration. A comparison of results in Brazil and Spain. Forest Ecol. Manage. 229, 247–258.

Duchelle, A.E., Guariguata, M.R., Less, G., Albornoz, M.A., Chavez, A., Melo, T., 2012. Evaluating the opportunities and limitations to multiple use of Brazil nuts and timber in Western Amazonia. Forest Ecol. Manage. 268, 39–48.

Guerra, F.G.P.Q., 2008. Contribuição dos produtos florestais não madeireiros na geração de renda na Floresta Nacional do Tapajós – Pará. Dissertação (Mestrado em Ciências Florestais)- Universidade Federal do Paraná, Curitiba, p. 133.

Herrero-Jáuregui, C., García-Fernández, C., Sist, P., Casado, M.A., 2011. Recruitment dynamics of two low-density neotropical multiple-use tree species. Plant Ecol. 212, 1501–1512.

Herrero-Jáuregui, C., Sist, P., Casado, M.A., 2012. Population structure of two low-density neotropical tree species under different management systems. Forest Ecol. Manage. 280, 31–39.

Homma, A.K.O., 2012. Plant extractivism or plantation: what is the best option for the Amazon? Estudos Avançados 26, 167–185.

IBGE, 1988. Mapa de Vegetação do Brasil. Ministério da Agricultura, Brasília, Brasil.

IBGE, 2011. Instituto Brasileiro de Geografia e Estatística. Available at: <http://www.ibge.gov.br/estadosat/perfil.php?sigla=pa#> (Last accessed date: 08.10.13).

Klimas, C.A., Kainer, K.A., Wadt, L.H., de, O., 2012. The economic value of sustainable seed and timber harvests of multi-use species: an example using *Carapa guianensis*. Forest Ecol. Manage. 268, 81–91.

Kluppel, M.P., Ferreira, J.C.P., Chaves, J.H., Hummel, A.C., 2010. Case study: in search of regulations to promote the sustainable use of NTFPs in Brazil. In: Laird, S.A., McLain, R., Wynberg, R.J. (Eds.), Wild Governance – Finding Policies that Work for Non-timber Forest Products. Earthscan, London, pp. 43–52.

Leite, A., Alechandre, A., 2001. Rigamonte-Azevedo, C., Campos, C.A., Oliveira, A., 2001. Recomendações para o Manejo Sustentável do Óleo de Copaíba. Rio Branco: Ufac/ Sefe, pp. 38.

Lima, M.R.F.D., Luna, J., De, S., Santos, A.F.D., Andrade, M.C.C.D., Santana, A.E.G., Genet, J.P., Marquez, B., Neuville, L., Moreau, N., 2006. Anti-bacterial activity of some Brazilian medicinal plants. J. Ethnopharmacol. 105, 137–147.

Martins, K., Herrero-Jáuregui, C., da Costa, P., Tonini, H., Bentes-Gama, M.de M., Vieira, A.H., Wadt, L.H.de O., 2012. Interspecific differences in the oleoresin production of *Copaifera* L. (Fabaceae) in the Amazon rainforest. Ann. Forest Sci. 70, 319–328.

Medeiros, R.D., Vieira, G., 2008. Sustainability of extraction and production of copaíba (*Copaifera multijuga* Hayne) oleoresin in Manaus, AM, Brazil. Forest Ecol. Manage. 256, 282–288.

Newton, P., Peres, C.A., Desmoulière, S.J.M., Watkinson, A.R., 2012b. Cross-scale variation in the density and spatial distribution of an Amazonian non-timber forest resource. Forest Ecol. Manage. 276, 41–51.

Newton, P., Watkinson, A.R., Peres, C.A., 2011. Determinants of yield in a non-timber forest product: *Copaifera* oleoresin in Amazonian extractive reserves. Forest Ecol. Manage. 261, 255–264.

Newton, P., Watkinson, A.R., Peres, C.A., 2012a. Spatial, temporal, and economic constraints to the commercial extraction of a non-timber forest product: Copaíba (*Copaifera* spp.) oleoresin in Amazonian reserves. Econ. Bot. 66, 165–177.

Pattanayak, S.K., Sills, E.O., 2001. Do tropical forests provide natural insurance? the microeconomics of non-timber forest product collection in the Brazilian Amazon. Land Econ. 77, 595–612.

Palisade Corporation, 2012. @RISK. Risk analysis and simulation add-in for Microsoft® Excel, Ithaca, NY USA.

Peters, C.M., 1996. The Ecology and Management of Non-Timber Forest Resources, World Bank Technical Paper No 322. World Bank, Washington, DC.

Phillips, O., Gentry, A.H., Reynel, C., Wilkin, P., Galvezdurand, C., 1994. Quantitative ethnobotany and Amazonian conservation. Conserv. Biol. 8, 225–248.

Pinto, A., Amaral, P., Gaia, C., Oliveira, W., 2010. Boas Práticas para Manejo Florestal e Agroindustrial – Produtos Florestais Não Madeireiros Belém: Imazon e SEBRAE, pp. 180.

Plowden, J.C., 2001. The ecology, management and marketing of non-timber forest products in the alto rio Guamá indigenous reserve (eastern Brazilian Amazon). Thesis (Doctor of Philosophy). The Pennsylvania State University. Pensilvania, 2001, pp. 264.

Plowden, C., 2003. Production ecology of copaíba (*Copaifera* spp.) oleoresin in the Eastern Brazilian Amazon. Econ. Bot. 57, 491–501.

Plowden, C., 2004. The ethnobotany of copaíba (*Copaifera*) oleoresin in the Amazon. Econ. Bot. 58, 729–739.

Radambrasil, 1983. Projeto RADAMBRASIL: 1973–1983, Levantamento de Recursos Naturais, Vols. 1–23. Ministério das Minas e Energia, Departamento Nacional de Produção Mineral (DNPM), Rio de Janeiro.

Ramirez, N., Arroyo, M.A., 1990. Estructura poblacional de Copaifera pubiflora Benth. (Leguminosae; Caesalpinioideae) en los Altos Llanos Centrales de Venezuela. Biotropica 22 (2), 124–132.

Rigamonte-Azevedo, O.C., Wadt, P.G.S., Wadt, L.H. de O, 2006. Potencial de produção de óleo-resina de copaíba (Copaifera spp.) de populações naturais do sudoeste da Amazônia. R. Árvore, 30(4), 583–591.

Rodriguez, L.C.E., Diaz-Balteiro, L., 2006. Régimen óptimo para plantaciones de eucalipto en Brasil: Un análisis no determinista. Interciencia 31, 739–744.

Romero, C., 2012. Short communication. Economics of natural resources: in search of a unified theoretical framework. Spanish J. Agric. Res. 10, 29–33.

Santos, A.O., Nakamura, T.U., Dias Filho, B.P., Veiga Junior, V.F., Pinto, A.C., Nakamura, C.V., 2008. Effect of Brazilian copaíba oils on *Leishmania amazonensis*. J. Ethnopharmacol. 120, 204–208.

Santos, A.J.dos, de Q. Guerra, F.G.P., 2010. Aspectos econômicos da cadeia produtiva dos óleos de andiroba (*Carapa guianensis* Aubl.) e copaíba (*Copaifera multijuga* Hayne) na Floresta Nacional do Tapajós – Pará. Floresta 40, 23–28.

Schulze, M., Grogan, J., Landis, R.M., Vidal, E., 2008. How rare is too rare to harvest? management challenges posed by timber species occurring at low densities in the Brazilian Amazon. Forest Ecol. Manage. 256, 1443–1457.

Shanley, P., da Silva, M.S., Melo, T., Carmenta, R., Nasi, R., 2012. From conflict of use to multiple use: forest management innovations by small holders in Amazonian logging frontiers. Forest Ecol. Manage. 268, 70–80.

Sobol, I.M., 1994. A primer in Monte Carlo Method. CRC Press, Boca-Raton, FL.

Ticktin, T., 2004. The ecological applications of harvesting non-timber forest products. J. Appl. Ecol. 41, 11–21.

Veiga Jr., V.F., Pinto, A.C., 2002. O Gênero *Copaifera* L. Química Nova 25, 273–286.