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# Financial Revenues from Timber Harvesting in Secondary Cloud Forests: A Case Study from Mexico

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**Abstract:** Secondary forests, i.e., those arising after the clearance and abandonment of previously forested land, dominate tropical forest landscapes, rapidly sequester carbon, provide essential ecosystem services and are prone to re-clearance. Secondary cloud forests (SCF) play a particularly critical role for biodiversity and hydrological regulation. To promote their persistence, sustainable management is necessary; however, there is limited information regarding SCF potential for sustainable timber production. We estimated the revenue from selective timber harvesting in a pilot study in a 20-year-old SCF in Mexico. We explored the effect of the harvested timber volume, harvesting costs and price of forest products on the Net Present Value (NPV). Small landowners could only extract 17% of the harvestable standing volume due to a high number of small trees, a high (34%) volume of non-timber species, and their limited capacity to process timber. A third of the income derived from fuelwood, and overall financial returns were negative. A positive NPV may result from a 20% harvesting intensity, a 10% reduction in harvesting costs, or a 20% increase in stumpage price. Our results warrant the development of forest policy instruments and economic incentives for small-scale SCF landowners to alleviate poverty and meet national and global restoration and climate mitigation goals.

**Keywords:** cost–benefit analysis; natural regeneration; net present value; forest restoration; selective timber harvesting; smallholders



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## 1. Introduction

Secondary forests (arising after clearance and abandonment of previously forested land) are increasingly important components of tropical landscapes [1]. They account for more than half of tropical forest cover, sequester large amounts of carbon in their biomass, regain biodiversity and provide timber and non-timber forest products [2–6]. The growing demand for timber in the tropics [7] and the concurrent importance of maintaining multiple forest functions, denote the urgency to promote sustainable management schemes for secondary forests [8,9]. However, regenerating forests in Latin America are frequently re-cleared shortly after the occurrence of natural regrowth [10]. In Costa Rica, 50% of secondary forest cover is re-cleared within 20 years of land abandonment [11] while, in the Brazilian Atlantic Forest, these forests last no more than an average of 8 years thereby challenging restoration efforts that rely on natural forest regrowth [12].

The long-term permanence of Secondary Cloud Forests (SCF) and their sustainable management in particular, is of great importance since they play a key role in hydrological regulation and soil retention, and as refuges of tropical montane biodiversity [13–16]. Although tropical montane cloud forests lost approximately 55% of their original cover worldwide, mostly through conversion for agricultural activities [13,17], their recovery via secondary succession following land abandonment has been widely detected across the globe [1,17,18]. Tropical montane cloud forest landscapes comprise a range of forests of varying successional age and structure. An increase in SCF cover has been reported over recent decades in Colombia [19], Venezuela [20], and Mexico [21]. In Mexico (the focus of this study), only ca. 55% of the original tropical montane cloud forest cover remains and, of this, 54% corresponds to SCF [22], although with significant fragmentation. Unplanned logging for timber, fuelwood and charcoal production is common among forest owners and rural inhabitants in these fragments [23–26]. Unsustainable logging in these patches further contributes to forest degradation and the depletion of locally valuable tree species [25,27], which can lead to complete deforestation [28].

Despite the importance of SCF, to our knowledge, no country in the Neotropics has developed programs to promote their sustainable use. Sustainable timber harvesting could add value to SCF, increasing the possibility of their permanence while potentially reducing conversion pressure on neighboring old-growth forests. However, timber production from secondary forests in general remains challenging due to legal impediments, a lack of appropriate government incentives for timber production and limited dissemination regarding their contributions to sustaining rural livelihoods, among other barriers [1,8,9,29,30]. The financial outcomes of timber harvesting are critical for forest owners to maintain sustainable use [31]. To this end, the economic return from SCF timber production must be able to outcompete alternative land uses. It remains to be determined whether the income from timber harvesting in SCF is sufficient to incentivize landowners to practice long-term management. The objective of this study was to analyze the financial outcomes from selective timber harvesting in a pilot case study involving SCF in Mexico. By performing a sensitivity analysis, we explored the effect of harvested timber volume, harvesting costs and the price of forest products on the Net Present Value. We discussed the challenges to the financial viability of timber production in SCF and alternatives to foster their sustainable management.

## 2. Materials and Methods

### *2.1. Study Area*

The pilot project concerning the sustainable management of SCF is located in central Veracruz, Mexico (19°11′23″ N, 96°59′11″ W; 1300 to 1500 m.a.s.l.). The region features remnants of old-growth and SCF immersed in a matrix of agricultural crops (including shade coffee plantations) and cattle pastures [23]. The mean annual temperature is 19.1 °C and the mean annual precipitation is 2100 mm. The original vegetation is tropical montane cloud forest ("bosque mesófilo de montaña" *sensu* Rzedowski 2006 [32]). The soil is an umbric Andosol [33].

In 1950, 270 ha were deforested in the study area for livestock production over a period of 45 years. Due to a high level of soil erosion in 1996, livestock was excluded from the grazing areas and natural forest regeneration ensued. This process generated forest patches of different sizes that together accounted for 98 ha of SCF [34]. The smallholder cooperative "Las Cañadas" defined the following management goals for the SCF in the area: (i) to maintain forest ecosystem functions (soil protection, reservoir of biodiversity, hydrological cycle), (ii) ensure sustainable production of timber and fuel wood, and (iii) serve as a source of local employment. A total of 106 ha was assigned to conservation (including a 30 ha fragment of old-growth cloud forest) while other areas were designated for multiple use (agriculture, intensive cattle grazing, tree plantations of native and exotic species). The studied SCF was 20 years old at the start of the project in 2016. The structure, tree diversity, composition and soil conditions in the old-growth forest fragment and the SCF are described elsewhere [35].

### *2.2. Forest Inventory*

To evaluate forest structure and estimate the growth and yield of standing timber, an inventory was conducted in 2016. In total, 30 circular sampling plots were established, each with a 1000 $m^2$ in area. In each plot, all trees ≥10 cm in diameter at breast height (DBH) were measured and their height was also recorded. The allometric equations used to estimate the volume for the different species are presented in Appendix A. During the inventory, several trees were recorded as remnant individuals of the original forest (Appendix B). Given their ecological importance, these remnant trees (≥55 cm DBH) were not harvested [36].

Considering the critical role of tropical montane cloud forests in the hydrological cycle and soil conservation [13,37], maintenance of a permanent forest cover is paramount and selective logging is recommended [38,39]. A 30% harvesting intensity of the stand volume (>10 cm DBH) was therefore prescribed.

To estimate the Mean Annual Increment (MAI), we used the standing volume excluding the remnant old trees (≥55 cm DBH) divided by 20 years, with the assumption that the present volume grew in 20 years (the age of the forest since the exclusion of cattle). Some of the limitations of this indirect estimation of the MAI are that the contribution of the remnant trees to forest growth was not considered and the growth rate per species could not be determined. The estimated MAI (excluding remnant trees) was 3.89 $m^3$ $ha^{-1}$ $year^{-1}$ and, based on this estimate and a 30% harvesting intensity, a 7.3 year cutting cycle was determined (return interval in years between timber harvests in the same area; Appendix C). After this period, the stands can be intervened again.

### 2.3. Timber Harvesting

The timber harvesting plan was authorized by the Secretary of the Environment and Natural Resources (SEMARNAT) in 2018. The intervened stand presented a total volume of 70.8 $m^3$ $ha^{-1}$ excluding the remnant trees (a value lower than the mean volume estimated for the whole SCF) and the authorized volume for harvesting was 21.3 $m^3$ $ha^{-1}$. However, the cooperative only applied a harvesting intensity of 17%. The reasons for this were that a high number of trees belonged to the 10–15 cm DBH category, 34% of the harvestable volume had no timber value, and the cooperative had a reduced technical and technological capacity for harvesting and processing timber. In addition, a preliminary financial analysis that included transporting roundwood and processing in a local sawmill indicated a very high cost. For this reason, the cooperative members sawed the logs with a hand-chainsaw instead of paying the sawmill fees and constructed a woodshed in which to dry the wood. The cost of transportation outside "Las Cañadas" is absorbed by the buyers.

The cutting cycle depends on the harvesting intensity. At the 17% harvesting intensity implemented, the stand volume is estimated to recover within 3.8 years (Appendix C). However, the cutting cycle was fixed at 7 years because the authorized management plan had established this scheme of intervention, and the cooperative decided to wait for the small trees to develop into commercially attractive diameters. A new inventory will need to be conducted to record the forest growth after the established period of time, in order to evaluate the SCF response to the interventions.

### 2.4. Cost–Benefit Analysis

To estimate the production costs, we included the following: fees for tree surveying (selection of trees that will be harvested), labour costs (felling, skidding, sawing, loading), maintenance costs for tools and equipment, fuel and consumables, investment in equipment and woodshed, and administrative costs (contracting services, sales negotiations). The consultant fee for tree selection and marking was USD 2/$m^3$ (only a certified consultant can select trees for harvesting on forested land in Mexico). The consultant had to mark all the trees for the authorized volume, as required by forest regulations (even though a smaller timber volume was extracted, as explained above), totaling USD 43 for the 21.3 $m^3$/ha authorized for the stand. Overall, USD 37.9 per $m^3$ of harvested timber was paid towards the felling, skidding, sawing, loading to a truck and unloading in the wood drying shed. These costs were recorded together with no estimation of the amount of labour assigned to each activity. Labour costs vary depending on stand structure, slope and distance, and training of the crew. In this case, the range in slope values was between 30–45% and the distance to the road was 75–125 m. The tools and equipment maintenance included expenses that would be incurred regularly (machetes, log grappling hooks, chain saw blades, chainsaw repair, earmuffs and boots for the crew). The cost of fuel and consumables (including petrol, oil to lubricate the chainsaw and additives, paint for marking out the sawing cuts, drag chains, chainsaw chains) was also included for every year of operation. The investment in equipment and infrastructure (chainsaws and wood drying shed) was included in the costs according to the linear depreciation. The lifetime for each chainsaw is 5 years and for the wood drying shed it is 20 years. Thus, the price was divided among the useful years of life considering a long-term operation. Timber harvesting was conducted by the members of the cooperative in 12 ha of forest in 2020, and in another 12 ha in 2021. Calculations of the production costs and profit were only made from the second year of the operation because many adjustments were made in the first year. All of the costs and income are reported per hectare per year.

The costs of the inventory and management plan production were not included because subsidies are available from the government to cover these expenses for land owners with a minimum forest area of 10 ha [40]. The amount subsidized by the government for inventory and management plans for the area would have been USD 2014. In the present case, however, the inventory and management plan were funded through an external agency. Costs associated with road construction and maintenance were not included. These can present a high variation depending on the location of the stands, and on the existence and condition of any roads. Subsidies for roads are also available from the government, although these are not always granted.

Prices for sawn wood per species in the regional market were obtained via direct contact with sawmills (Appendix D). The prices for timber after processing (of commercial dimensions) of the most abundant species were as follows (USD per footboard): *Quercus* spp. = 0.5, *Liquidambar styraciflua* = 0.5, *Clethra mexicana* = 0.3, *Trema micrantha* = 0.3, common species = 0.2 (this category includes various species commonly found in natural regenerated forests). Non-timber species were also present, but the majority of these can be used for fuelwood (species uses are shown in Table 2). A 50% lumber yield was estimated, as reported for tropical timber in Mexico [41]. The profit from fuelwood and other products (e.g., oak trunks used for the cultivation of mushrooms) was also included because these are important resources for rural communities [42]. The price of fuelwood was USD 25 per $m^3$. To calculate the annual profit, the price per species was applied to the harvested volume of each species, which varied depending on the standing volume of that species. The price of timber and fuelwood was that at the road.

To assess the economic viability of the operation, we calculated the Net Present Value (NPV) based on an annual discount rate of 10% (interest rate of FONAFOR, Mexican Forestry Fund created to induce timber production projects). For the NPV calculations, the production costs and income occurred annually, since a different area would be harvested every year. Calculation of the NPV of a rotation on a fixed piece of land did not reflect the operation in Las Cañadas because the forest area was subdivided to harvest a different forest area each year. As described by Cubbage et al. [43], community forestry enterprises in Mexico periodically harvest different parts of a natural forest. NPV was calculated based on a period of 7 years because, as explained earlier, the cooperative had to maintain the authorized cutting cycle and a new inventory and operation would be implemented at the end of this period. In the year 0, all of the costs were included with no inflow and in year 7 there was no outflow because all of the costs incurred were included in the previous year. An exchange rate of USD 1 = 20 Mexican pesos was used.

The forest structure attributes and estimated growth rate are presented in Table 1. Approximately 4.4% of the trees correspond to remnant trees ($\geq$55 cm DBH) and 71.4% are in the 10 to 24 cm DBH categories (Appendix B). Remnant trees accounted for 23.2% of the total volume. Based on the MAI estimated from the standing volume excluding the remnant trees (3.89 $m^3$ $ha^{-1}$ $year^{-1}$), with harvesting intensities of 10%, 17%, 20% and 30%, the cutting cycles estimated were 2.2, 3.8, 4.6 and 7.3 years, respectively (Appendix C).

**Table 1.** Attributes of the 20-year old secondary cloud forest (mean ± SE) in Mexico. The standing volume was calculated including and excluding remnant old trees (≥55 cm DBH).

| Forest Attributes | Estimated Values |
|---|---|
| Density (no. trees/ha) | 269.6 ± 13.7 |
| Basal area ($m^2$/ha) | 12.4 ± 1.2 |
| Standing volume including all trees ($m^3$/ha) | 104.5 ± 16.9 |
| Standing volume ($m^3$/ha) * | 75.7 ± 13.6 |
| Mean annual increment ($m^3$ $ha^{-1}$ $year^{-1}$) * | 3.78 ± 0.68 |

* Excluding remnant old trees.

We used sensitivity analyses to assess how variations in the harvested timber volume, production costs and timber price could affect the financial indicators. To estimate the effect of harvested timber volume on the financial indicators, we used the following scenarios: 10%, 17% (Las Cañadas), 20% and 30% harvesting intensity. For these scenarios, the cutting cycle was adjusted according to the harvesting intensity (Appendix C). Since tree surveying costs could be reduced by applying for a permit for the actual volume of timber harvested, we calculated the financial indicators with the cost of marking only the volume harvested. Given that harvesting costs per unit of wood are inversely related to the volume of timber harvested [43,44], we estimated the adjustment to the harvesting costs (labour, tools and equipment maintenance, fuel and consumables) per $m^3$, depending on the volume of timber based on a regression equation calculated from the study of Cubbage et al. [43] (see Appendix E). However, the data were not directly comparable and the modification estimated was very small; we therefore used the same costs structure, adjusting proportionally for the different volume of timber harvested. The proportion of sawn timber and fuelwood produced was maintained constant across the different volumes harvested. Investment in equipment and a woodshed and the administration fee were included as fixed costs (i.e., they did not vary with the volume of timber harvested).

**Table 2.** Tree species in 20 year-old secondary cloud forest, Veracruz, Mexico, in decreasing order of volume (includes remnant old trees). Conservation status: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near Threatened and LC = Least Concern [45]. Uses: Cha = charcoal, Fue = fuelwood, Fruit = fruit edible, Tim = timber, Timb int = timber for interiors, na = not available information.

| Species | Family | Status | Vegetation | Volume ($m^3$/ha) | Uses |
|---|---|---|---|---|---|
| *Quercus sapotifolia* Liebm. | Fagaceae | VU | Cloud forest | 37.7 | Tim, Cha |
| *Trema micrantha* (L.) Blume | Cannabaceae | LC | Cloud forest | 14.9 | Tim |
| *Liquidambar styraciflua* L. | Altingiaceae | LC | Cloud forest | 8.5 | Tim |
| *Myrsine coriacea* (Sw.) R.Br. ex Roem. & Schult. | Myrsinaceae | LC | Cloud forest | 8.1 | Fue |
| *Quercus xalapensis* Bonpl. | Fagaceae | CR | Cloud forest | 7.2 | Tim, Cha |
| *Quercus lancifolia* Schltdl. & Cham. | Fagaceae | NT | Cloud forest | 6.6 | Tim, Cha |
| *Clethra mexicana* DC. | Clethraceae | LC | Cloud forest | 5.6 | Tim |
| *Quercus insignis* M.Martens & Galeotti | Fagaceae | CR | Cloud forest | 3.6 | Tim, Cha |
| *Frangula capreifolia* Schltdl | Rhamnaceae | LC | Cloud forest | 2.5 | na |
| *Croton draco* Schltdl. & Cham. | Euphorbiaceae | LC | Secondary | 1.7 | Fuel |
| *Acacia pennatula* (Schltdl. & Cham.) Benth. | Fabaceae | | Early secondary vegetation | 1.6 | Fuel |
| *Brunellia mexicana* Standl. | Brunelliaceae | LC | Cloud forest | 1.5 | Tim |
| *Lippia myriocephala* Schltdl. & Cham. | Verbenaceae | LC | Secondary | 0.7 | Fue |
| *Eugenia xalapensis* (Kunth) DC. | Myrtaceae | VU | Cloud forest | 0.5 | na |
| *Ocotea psychotrioides* Kunth | Laurceae | EN | Cloud forest | 0.4 | na |

**Table 2.** *Cont.*

| Species | Family | Status | Vegetation | Volume ($m^3$/ha) | Uses |
|---|---|---|---|---|---|
| *Saurauia leucocarpa* Schltdl. | Actinidiaceae | VU | Cloud forest | 0.31 | Fruit |
| *Zanthoxylum riedelianum* Engl. | Rutaceae | | Secondary tropical forest | 0.3 | Tim |
| *Quercus candicans* Née | Fagaceae | VU | Cloud forest | 0.2 | Tim, Cha |
| *Citharexylum* sp. | Verbenaceae | | | 0.1 | na |
| *Quercus paxtalensis* C.H.Mull. | Fagaceae | CR | Cloud forest | 0.1 | Tim, Cha |
| *Toxicodendron striatum* (Ruiz & Pav.) Kuntze | Annacardiaceae | | Secondary tropical forest | 0.1 | na |
| *Heliocarpus appendiculatus* Turcz. | Malvaceae | LC | Cloud forest | 0.1 | Tim int |
| *Vismia* sp. | | | | 0.07 | na |
| *Beilschmiedia mexicana* (Mez) Kosterm. | Lauraceae | EN | Cloud forest | 0.06 | Tim |
| *Hedyosmum mexicanum* C. Cordem. | Chloranthaceae | LC | Cloud forest | 0.04 | Fruit, |
| *Vernonathura patens* (Kunth) H. Rob. | Asteraceae | | Secondary tropical forest | 0.03 | Cha, Med |
| *Styrax glabrescens* Benth. | Styracaceae | VU | Cloud forest | 0.02 | na |
| *Siparuna* sp. | Siparunaceae | | | 0.01 | na |

We also assessed the effect of changes in production costs for the actual timber harvesting volume in Las Cañadas as follows: we calculated a 10% and 20% decrease and increase in the total costs, which could be affected by distance to roads, training of workers and the effect on the efficiency of harvesting activities, as well as changes in the price of fuel and wages over time due to inflation. For this analysis, the volume of timber harvested in Las Cañadas was considered.

We evaluated the effect of timber prices on the economic viability of the project by applying a 10% and 20% decrease and increase in the timber price, which varies depending on the species, timber quality and market. The volume of timber and the cost structure used were taken from Las Cañadas without modification.

## 3. Results

### *3.1. Forest Inventory*

A total of twenty three tree species and five morphospecies were recorded and their uses and category of threat are shown in Table 2. Three species are classified as critically endangered, two as endangered and five as vulnerable [45]. The most abundant tree species (in decreasing order of abundance) were *Quercus sapotifolia*, *T. micrantha*, *L. styraciflua*, *Myrsine coriacea*, *Q. xalapensis*, *Q. lancifolia* and *C. mexicana*. Most of the dominant species are of intermediate successional affinity, apart from *T. micrantha* and *M. coriacea* of early successional affinity. Remnant trees (≥55 cm DBH) of the following species were recorded: *C. macrophylla*, *L. styraciflua*, *Q. insignis*, *Q. lancifolia*, *Q. sapotifolia* and *Q. xalapensis*.

### *3.2. Revenue from Timber and Fuelwood*

Although the authorized harvesting intensity was 30%, the cooperative only extracted 11.7 $m^3$ $ha^{-1}$, equivalent to a 17% harvesting intensity, as explained above. From this, 1.9 $m^3$ $ha^{-1}$ of sawn wood and 9.1 $m^3$ $ha^{-1}$ of fuel wood were produced. The high volume of fuelwood was due to the poor or irregular conformation of the trees and abundance of non-timber species.

The production costs and profit made from timber and fuelwood harvested per hectare are shown in Table 3. Payments to workers for felling, skidding, sawing and loading activities accounted for 57% of the production costs, while fuel and consumables accounted for 20%, tree selection and marking for 5%, and administration for 8%. Approximately 28% of the income was from fuelwood and other products; these were derived from harvesting non-timber species, poorly formed trees and timber harvesting waste. An annual profit of USD 24 $ha^{-1}$ was made and based on the analysis for a period of 7 years, the NPV was negative.

**Table 3.** Production costs and financial returns from sawn timber and fuelwood with a 7-year cutting cycle in secondary cloud forest. Production costs and income occurred every year since a different area is harvested every year. The volume of wood harvested was 11.7 $m^3$ $ha^{-1}$ and the harvesting intensity applied was 17% of the standing volume (excluding remnant old trees). Amounts in USD are rounded up. NPV = net present value, IRR = internal rate of return (IRR). NPV and IRR are estimated considering a 10% discount rate. Labour includes felling, skidding, cut logging, sawing and loading. Sawn wood includes different prices for multiple species and commercial and secondary products.

| | Year 0 | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 |
|---|---|---|---|---|---|---|---|---|
| Production costs | | | | | | | | |
| Inventory and management plan | - | - | - | - | - | - | - | |
| Tree marking (USD/ha) | 43 | 43 | 43 | 43 | 43 | 43 | 43 | |
| Labour (USD/ha) | 443 | 443 | 443 | 443 | 443 | 443 | 443 | |
| Tools and equipment maintenance (USD/ha) | 32 | 32 | 32 | 32 | 32 | 32 | 32 | |
| Fuel and consumables (USD/ha) | 155 | 155 | 155 | 155 | 155 | 155 | 155 | |
| Investment in equipment and infrastructure (USD/ha) | 45 | 45 | 45 | 45 | 45 | 45 | 45 | |
| Administration (USD/ha) | 62 | 62 | 62 | 62 | 62 | 62 | 62 | |
| Total costs (USD/ha) | 780 | 780 | 780 | 780 | 780 | 780 | 780 | |
| Wood, fuelwood, and other products | | | | | | | | |
| Revenue from sawn wood (USD/ha) | | 577 | 577 | 577 | 577 | 577 | 577 | 577 |
| Revenue from fuelwood (USD/ha) * | | 227 | 227 | 227 | 227 | 227 | 227 | 227 |
| Profit (USD/ha) | −780 | 24 | 24 | 24 | 24 | 24 | 24 | 804 |
| NPV (ha) | | | | | | | | −261 |
| IRR (%) | | | | | | | | 3 |

* and other products.

The sensitivity analysis to consider the uncertainties of key variables showed that the NPV became positive under a 20% harvesting intensity scenario with a 5 year cutting cycle, and a considerable increase was observed in the estimated profit and NPV under a 30% harvesting intensity with a 7 year cutting cycle (Table 4). An increase in harvesting intensity also means that more benefits would be generated in terms of employment due to the requirement for more labour. For all of these scenarios, the tree marking cost considered was for the volume of actual timber harvested, and an increase in the annual profit occurred although the NPV remained negative under 10% and 17% harvesting intensities.

**Table 4.** Financial indicators from variation in harvesting volume based in Las Cañadas. NPV = Net Present Value, IRR = Internal Rate of Return. Amounts in USD are rounded up. The cost of tree marking used is for the volume harvested.

| | Harvesting Intensity Scenarios | | | |
|---|---|---|---|---|
| | 10% | 17% | 20% | 30% |
| Cutting cycle (years) | 2 | 4 | 5 | 7 |
| Harvesting volume ($m^3$/ha) | 7.1 | 11.7 | 14.2 | 21.3 |
| Production costs | | | | |
| Tree marking (USD/ha) | 14 | 23 | 28 | 43 |
| Labour (USD/ha) | 269 | 443 | 537 | 806 |
| Tools and equipment maintenance (USD/ha) | 19 | 32 | 38 | 58 |
| Fuel and consumables (USD/ha) | 94 | 155 | 187 | 281 |
| Investment in equipment and infrastructure (USD/ha) | 45 | 45 | 45 | 45 |
| Administration (USD/ha) | 62 | 62 | 62 | 62 |
| Total costs (USD/ha) | 503 | 760 | 898 | 1294 |

**Table 4.** *Cont.*

| | Harvesting Intensity Scenarios | | | |
|---|---|---|---|---|
| | **10%** | **17%** | **20%** | **30%** |
| Wood, fuelwood, and other products | | | | |
| Revenue from sawn wood (USD/ha) | 330 | 577 | 659 | 989 |
| Revenue from fuelwood (USD/ha) * | 129 | 227 | 259 | 388 |
| Profit (USD/ha) | −16 | 44 | 75 | 166 |
| NPV (ha) | −47 | −103 | 5 | 180 |
| IRR (%) | −3 | 6 | 8 | 13 |

* and other products.

The sensitivity analysis of the variation in production costs (with 17% harvesting intensity) showed that the NPV could be positive with a reduction of 10% in total costs (Table 5). Interestingly, an adjustment of the tree marking fee covering the actual volume of timber harvested (and no more), in combination with a reduction of 10% only in the costs of labour, produced an annual profit of USD 88 $ha^{-1}$, with an NPV of 79 and an IRR of 12%. In contrast, an increase of 10% in the total production costs resulted in loss and led to a marked decline in NPV.

**Table 5.** Financial indicators from increased and decreased of production costs and timber price based on a case study in Las Cañadas. NPV = Net Present Value, IRR = Internal Rate of Return.

| | **Production Costs Scenarios** | | | |
|---|---|---|---|---|
| | **−20%** | **−10%** | **+10%** | **+20%** |
| NPV | 656 | 249 | −565 | −973 |
| IRR (%) | 32 | 17 | −4 | −12 |
| | **Timber Price Scenarios** | | | |
| | **−20%** | **−10%** | **+10%** | **+20%** |
| NPV | −846 | −565 | −3 | 278 |
| IRR (%) | −13 | −5 | 10 | 17 |

Examining sensitivity to market change, we found that the estimated NPV could be positive with a 20% increase in timber price (with no modification in harvesting intensity or production costs; Table 5). However, the analysis also showed that a decrease of 10% in timber price would have a strong negative impact on the NPV.

## 4. Discussion

To achieve social and ecological benefits from forest management, sufficient financial returns for landowners must be secured. The results from the case study show that the production of timber from SCF via selective logging has limited financial viability under the current conditions at Las Cañadas for various reasons. Since we reported on a single case study with limited spatial and temporal replication, our results should be interpreted accordingly; however, the structure and composition of the studied forest falls within the range of those reported by the National Forest Inventory for SCF [22] and in previous studies [14,16,46]. The sensitivity analyses of the variables affecting the economic viability of the timber harvesting operation allowed us to identify important challenges and the effect of overcoming these challenges on the sustainable management of SCF, as discussed below.

### *4.1. Forest Growth and Volume of Commercial Timber*

The studied SCFs display high growth rates, but the low commercial volume due to the predominance of trees of small DBH, prevalence of non-timber species and timber species of very low stumpage price were found to be important constraints for profitability. The stand volume in the studied SCF corresponds to those reported for secondary lowland forest of similar age elsewhere [30,47]. Based on the Mexican National Forest Inventory data for the period 2009–2014, a stand volume of 78.8 $\pm$ 8.4 $m^3$/ha (trees $\geq$ 10 cm DBH) for SCF was estimated (category "arboreal"; [22]). The MAI values estimated in the studied forest fall within the range reported for similar systems of 3.19 $m^3$ $ha^{-1}$ $year^{-1}$ for SCF, according to the Mexican National Forest Inventory [22]; 4.90 $m^3$ $ha^{-1}$ $year^{-1}$ in 22.5 year-old tropical montane wet forest; 6.68 $m^3$ $ha^{-1}$ $year^{-1}$ in tropical premontane wet forest in the Neotropics [47], and also in tropical secondary forests located at lower elevations in Paraguay, Brazil and Costa Rica [4]. While stand growth is important, the species present different growth rates and prices, which can affect the economic result. Although it was not possible to determine the growth rate per species, previous studies in SCF report rapid growth rates in *Liquidambar styraciflua* (0.71 cm $year^{-1}$) and *Quercus xalapensis* (0.91 cm $year^{-1}$) [48], which are among the most abundant species in the studied SCF. The abundant *Trema micrantha* also displays rapid growth (0.95 cm $year^{-1}$) [49] but its price is lower, and *M. coriacea* is also fast-growing but non-commercial. Since secondary forests are generally characterized by high heterogeneity in structure and composition, an analysis of forest growth in sites of different ages and conditions is necessary to maximize yield by adjusting the harvesting age and cutting cycles according to the particular site conditions and species composition.

The improvement in financial indicators observed with an increased harvest volume and the corresponding cutting cycle suggest that a higher harvesting intensity and earlier return of the investment could contribute to financial viability. However, the increase in harvesting intensity is limited by the availability of timber species and larger trees. Since timber harvesting costs per unit are inversely related to the volume of timber harvested [43,44], with higher harvesting costs for small-diameter trees [50], the labour costs per unit of sawn timber produced are high in the studied SCF. Based on polycyclic management, older secondary tropical forests (40–60 years) with higher volumes are considered to have more potential for timber production [51]. However, early returns are necessary to avoid the re-clearing of the SCF. It is important to recognize that the financial analysis suggests that the system starts at year 0, although in reality the system started 20 years earlier, at the moment of pasture abandonment. The forgone income for the landowners from alternative land use, such as cattle production or agriculture, during the period of SCF development was not included. An analysis of rotation cycles in plantations in Vietnam showed that, while smallholders could derive higher financial benefits from longer rotation ages, their need for quick returns meant that they could not invest in long-term outcomes [52].

Enhancing timber productivity in secondary forests could potentially increase their value while fostering other ecosystem services and reducing pressure on remnant forests. To improve the stock of timber species, silvicultural interventions have been recommended, including enrichment planting and a reduction in competition for valuable trees [53,54]. Experimental enrichment plantings with shade tolerant species demonstrated 80% survival after three years in SCF [55]. A study of the effects of thinning on trees ($\geq$10 cm DBH) in 30 year old secondary montane oak forest in Costa Rica showed that mortality rates were higher in the control than in a stand with thinning (0.58% and 0.19%, respectively) and thus the thinning contributed to higher stability [56]. In this sense, further research to assess SCFs' response to silvicultural interventions is required. However, the management alternatives depend on the possibility to generate extra income and, under the prevalent conditions, such practices are unaffordable for SCF owners. Other research gaps and barriers to advance in SCF management have recently been assessed elsewhere [9].

### *4.2. Production Costs and Incentives*

The costs of compliance with the current regulations for timber harvesting are very high, especially for smallholders. Since there are no guidelines for timber harvesting in secondary forests in Mexico, their management must conform to the requirements for mature forests (with high costs of forest inventory and management plan production, as well as strict procedures for harvesting established volumes per species). Considering that such strict restrictions on logging SCF can have negative effects on the maintenance of forest cover and rural development, a flexible legal framework for SCF management must be created. The production and harvesting costs could be reduced by relaxing the requirement to strictly adhere to the initial management plan; for example, the cost of tree surveying could be reduced so that landowners are able to make decisions depending on their context and as they learn how best to manage the forest. Such an approach should be accompanied by programs aimed at technical capacity building to strengthen the ability of smallholders to manage their young forests, especially considering that the low levels of education and skills prevalent among workers possibly contribute to low efficiency. The limited availability of suitable equipment and lack of training for operations also contribute to high production costs by reducing efficiency (in the case study, renting equipment for transformation was too expensive and therefore a hand-chainsaw was used to saw the logs). Forest practices in the tropics often exhibit low productivity and efficiency as a result of outdated technologies [57]. The formation of forest owner associations that share equipment and administration services could be strategic in terms of reducing costs.

Our analysis supports the need for appropriate incentives and financial compensation schemes to maintain the sustainable use of SCF. If forest owners do not derive sufficient financial returns from harvesting timber and non-timber products, deforestation and forest degradation are expected because of the higher opportunity costs associated with more profitable agricultural land use. This is supported by the low NPV of SCF management in Las Cañadas. For development of the payment for the hydrological services program, an average annual profit of USD 66/ha for livestock production was estimated for Mexico in 2002 [58] and, for the region of Sierra Norte de Puebla, the opportunity costs for the agriculture and cattle potential land uses were USD 90 ha per year in 2011 [59]. To estimate the opportunity costs of the Reducing Emissions from Deforestation and Forest Degradation program (REDD+), the annual income from rain-fed agriculture for maize (Mexico's staple food crop) ranged from USD 18 to 93/ha [60]. A comparison of land-use alternatives in the tropics shows that cattle pasture generates higher net benefits than forestry [61]. To increase the attractiveness of SCF management, higher revenues from the provision of forest goods and services are required through external financing. Since multiple functions and values of forests are being increasingly recognized with promising financing sources, instruments and mechanisms at global and national levels [57], these could provide opportunities for the sustainable management of SCF. In this sense, a joint production of timber and compensatory schemes for hydrological services or carbon sequestration could foster the management of SCF. In Ecuador, for example, compensation payments for carbon sequestration are more effective when applied to the natural regrowth of secondary forests than to the establishment of plantations, due to lower costs and the relative early timber revenue [61]. An additional measure could be to pay higher incentives for management plans that include an increase in stock. Forests with higher stock will lead to improvements in both economic profitability and ecological forest functions. To this aim, knowledge is required regarding growth rates and carbon accumulation of SCF related to forest age. Based on such information, the change in NPV with varying forest age and timber volume could be estimated to determine which age or volume of SCF management for timber production could be most profitable. These values could then be compared with opportunity costs in order to derive compensation or incentive schemes.

### *4.3. Limited Market, Low Prices and Added Timber Value*

The low economic feasibility of the studied SCF is also due to the presence of many non-timber species and species with low market value. Pine timber has a better market price and value chains than SCF species. However, pine plantations do not support the same biodiversity as mixed plantations with cloud forest species [62,63]. In the case study, for example, *Q. sapotifolia* was highly abundant and fast growing and its timber is considered of high quality [64], but it reaches lower prices than pine timber. However, oaks are abundant in SCF, their timber can reach good prices and they are also used to produce charcoal, an important energy source for rural communities in Mexico [42]. Improving the management, processing and marketing for oaks presents potential for increasing benefits for forest owners. Abundant fast growing species such as *L. styraciflua*, *C. mexicana* and *T. micrantha* also have good timber properties, and many other species (some with reported good properties) fetch very low prices and are difficult to sell in Mexico. Markets must therefore be developed for the lesser-used species (e.g., the initiative Lesser Known Timber Species by the Forest Stewardship Council). Recent efforts to promote the commercialization of lesser-used species have been made in Mexico, including a published collection of timber species data which include many SCF species [64].

In addition, securing access to the market and improving the timber value from SCF species could increase the benefits for forest owners. Sustainable wood value chains that can generate premium prices for sustainable products must be developed. Another important element is added value through further processing [65]. In the case study, transformation to add value was undertaken by the cooperative as a means by which to increase the profit, and to find buyers aware of the important role of SCF. Promoting innovation in technology to dry wood could contribute to increased benefits for the landowners given that community forestry enterprises with sawmills have greater profits per $m^3$ in Mexico [43]. While all these alternatives could have an impact, to generate rural development benefits, value chain analysis would allow for a better understanding of the constraints that must be addressed in order to improve the functioning of the chain and prioritize interventions [65].

### *4.4. Multiple Use*

Given the low income from timber harvesting derived from SCF, a multiple use approach could include the harvesting of non-timber forest products (NTFP), some of which are presently produced and harvested (i.e., edible mushrooms, ornamental tree ferns, as well as wild-bee honey). However, it should be pointed out that tradeoffs involved in production and harvesting of multiple forest products often need careful consideration both from a biophysical and socioeconomic dimensions [66]. Therefore it would be necessary to analyze the costs and benefits derived from NTFP production and harvesting in the calculations of NPV. Such research, in conjunction with the analysis of a variety of production systems (i.e., varying in area, timber harvesting intensity, organization) would help to assess whether the diversified management of SCF is financially advantageous for landowners in the long term. Although NTFP harvesting for commercialization in Mexico faces complex legal restrictions [67], both timber and NTFP could become complementary sources of income. Overall, SCF can provide various services and policy fostering multiple use management is therefore required to alleviate poverty and to meet national and global restoration and climate mitigation goals.

## 5. Conclusions

SCF can provide multiple resources and benefits such as timber and fuel wood, regulation of hydrological cycle, climate change mitigation and contributions to the livelihoods of rural communities. However, timber production in our case study showed negative financial returns. Positive financial returns may be achieved if support is provided for forest owners to reduce production costs, and to obtain higher profits from better timber prices. Given the high diversity and low income from SCF timber harvesting, optimization of cutting cycles, improvement in the technical capacities for better efficiency and multiple use of resources are valid strategic measures. To avoid re-clearing and preserve diversity in these valuable systems, the development of multiple use management strategies, programs enhancing value chains, effective policy instruments and economic incentives for small-scale landowners to practice a sustained production of timber are necessary.

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## Appendix A

**Table A1.** Equations used to estimate the volume of timber for tree species in secondary cloud forest using tree diameter (DN) and height (A). The volume includes the trunk and branches.

| Forest Attributes | Estimated Values | Source |
|---|---|---|
| *Acacia pennatula* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Beilschmiedia mexicana* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Citharexylum affine* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Heliocarpus appendiculatus* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Lippia myriocephala* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Ocotea psychotrioides* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Quercus xalapensis* | EXP(−9.7852 + 2.19788 × LN(DN) + 0.63077 × LN(A)) | 1 |
| *Quercus candicans* | EXP(−9.7852 + 2.19788 × LN(DN) + 0.63077 × LN(A)) | 1 |
| *Saurauia leucocarpa* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Styrax glabrescens* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Trema micrantha* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Zanthoxylum riedelianum* | EXP(−9.3156 + 2.38434 × LN(DN) + 0.16699 × LN(A)) | 1 |
| *Quercus insignis* * | EXP(−9.412181 + 1.703762 × LN(DN) + 1.094561 × LN(A)) | 2 |
| *Quercus paxtalensis* | EXP(−9.412181 + 1.703762 × LN(DN) + 1.094561 × LN(A)) | 2 |
| *Quercus lancifolia* | EXP(−9.412181 + 1.703762 × LN(DN) + 1.094561 × LN(A)) | 2 |
| *Brunellia mexicana* | EXP(−9.4121801 + 1.7037616 × LN(DN) + 1.0945611 × LN(A)) | 3 |
| *Eugenia* sp. | EXP(−9.4121801 + 1.7037616 × LN(DN) + 1.0945611 × LN(A)) | 3 |
| *Frangula capreifolia* | EXP(−9.4121801 + 1.7037616 × LN(DN) + 1.0945611 × LN(A)) | 3 |
| *Hedyosmum mexicanum* | EXP(−9.4121801 + 1.7037616 × LN(DN) + 1.0945611 × LN(A)) | 3 |
| *Myrsine coriacea* | EXP(−9.4121801 + 1.7037616 × LN(DN) + 1.0945611 × LN(A)) | 3 |
| *Siparuna* sp. | EXP(−9.4121801 + 1.7037616 × LN(DN) + 1.0945611 × LN(A)) | 3 |
| *Toxicodendron striatum* | EXP(−9.4121801 + 1.7037616 × LN(DN) + 1.0945611 × LN(A)) | 3 |
| *Vernonathura* sp. | EXP(−9.4121801 + 1.7037616 × LN(DN) + 1.0945611 × LN(A)) | 3 |
| *Vismia* sp. | EXP(−9.4121801 + 1.7037616 × LN(DN) + 1.0945611 × LN(A)) | 3 |
| *Croton draco* | EXP(9.7891527 + 1.88887745 × LN(DN) + 1.004457398 × LN(A)) | 4 |
| *Clethra mexicana* | 0.0000655 × DN^1.6963297 × A^1.2083606 + 0.0000196 × DN^2 | 5 |
| *Liquidambar styraciflua* | 0.0000243 × DN^2.3470853 × A^0.7039852 + 0.0000674 × DN^2 | 5 |
| *Quercus sapotifolia* * | 0.0000604 × DN^2.018078 × A^0.7893415 + 0.0000535 × DN^2 | 5 |

1: CONAFOR (2015) Inventario Estatal Forestal y de Suelos–Estado de México 2014. 2: Inventario Forestal del Estado de Oaxaca, SARH, 1985. 3: Secretaría de Agricultura y Recursos Hidráulicos. 1976. Subsecretaria forestal y de la fauna Dirección general de inventario forestal Inventario forestal del estado de San Luis Potosí Publicación número 49, Mexico. 4: Inventario Forestal y de Suelos del Estado de Veracruz. 5: SiBiFor (2019) Modelos Biometricos Nacionales. * Given the lack of allometric equations for *Q. sapotifolia* and *Quercus insignis*, the model for *Quercus laurina* (the most similar species for which data is available) was used (SiBiFor 2019).

## Appendix B

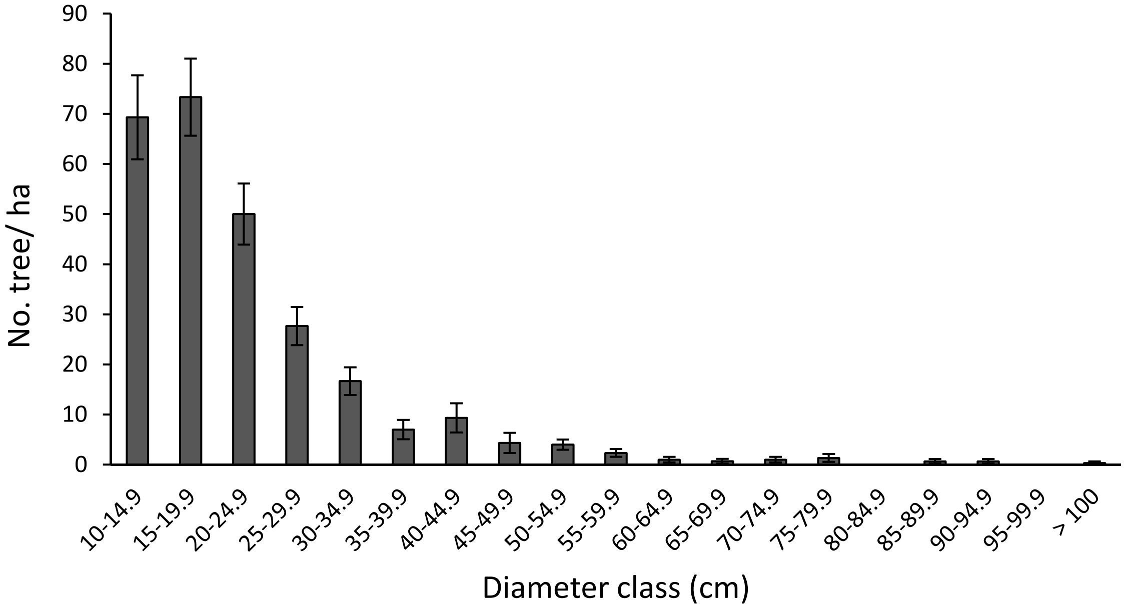


**Figure A1.** Distribution of trees in categories of diameter at breast height (DBH) in the secondary cloud forest. Trees ≥ 55 cm in DBH correspond to remnant old trees.

## Appendix C

The cutting cycle was calculated with the following formula:

CC = (log Standing volume–log Remnant volume)/log1.0 Relative increment
CC = cutting cycle
Standing volume = 75.681 $m^3$ $ha^{-1}$
Mean annual increment (MAI) = 3.78 $m^3$ $ha^{-1}$ $y^{-1}$
Relative increment 3.78/75.681 = 0.05.

**Table A2.** Cutting cycle estimated considering different harvesting intensity. Calculations based on the MAI, excluding remnant trees (≥55 cm DBH).

| Harvesting Intensity (%) | Cutting Cycle (Years) |
|---|---|
| 10 | 2.2 |
| 17 | 3.8 |
| 20 | 4.6 |
| 30 | 7.3 |

## Appendix D

**Table A3.** Table Price of lumber timber from secondary cloud forest tree species in Mexico in 2019. Prices obtained from regional sawmills.

| Species | Family | Foot Board (USD) |
|---|---|---|
| *Acacia pennatula* | Fabaceae | 0.2 |
| *Beilschmiedia mexicana* | Lauraceae | 0.2 |
| *Brunellia mexicana* | Brunneliaceae | 0.3 |
| *Citharexylum affine* | Verbenaceae | 0.2 |
| *Clethra mexicana* | Clethraceae | 0.3 |
| *Croton draco* | Euphorbiaceae | 0.3 |
| *Eugenia xalapensis* | Myrtaceae | 0.2 |
| *Hedyosmum mexicanum* | Chloranthaceae | 0.3 |

**Table A3.** *Cont.*

| Species | Family | Foot Board (USD) |
|---|---|---|
| *Heliocarpus appendiculatus* | Malvaceae | 0.3 |
| *Liquidambar styraciflua* | Altingiaceae | 0.5 |
| *Myrsine coriacea* | Primulaceae | 0.2 |
| *Ocotea psychotrioides* | Lauraceae | 0.3 |
| *Quercus candicans* | Fagaceae | 0.5 |
| *Quercus insignis* | Fagaceae | 0.5 |
| *Quercus lancifolia* | Fagaceae | 0.3 |
| *Quercus paxtalensis* | Fagaceae | 0.5 |
| *Quercus sapotifolia* | Fagaceae | 0.3 |
| *Quercus xalapensis* | Fagaceae | 0.5 |
| *Saurauia leucocarpa* | Actinidiaceae | 0.2 |
| *Styrax glabrescens* | Styracaceae | 0.2 |
| *Trema micrantha* | Cannabaceae | 0.3 |
| *Vernonanthura patens* | Asteraceae | 0.2 |
| *Vismia mexicana* | Hypericaceae | 0.2 |
| *Zanthoxylum riedelianum* | Rutaceae | 0.3 |

## Appendix E

The data published by Cubbage et al. [43] for volume of sawn timber and harvesting costs for 30 community forestry operations in Mexico were used to calculate a regression equation to adjust the harvesting costs depending on volume harvested: $y = -0.0154x + 633.56$, $R^2 = 0.144$. However, the volume of timber from Las Cañadas was much lower than the lowest value used by Cubbage et al. (192 $m^3$/yr), the harvesting costs estimated for Las Cañadas including labour, tools and equipment and fuel and consumables were much lower (USD 53.84/$m^3$) than the value obtained from the data reported in Cubbage et al., and the variation in the volume harvested for the scenarios we analyzed was considerably small compared to the values registered by Cubbage et al. Since the data were not directly comparable and the modification estimated was very small, we used the structure of costs without adjusting the harvesting costs depending on the volume of timber produced.

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