European Journal of Forest Research (2022) 141:665–681
https://doi.org/10.1007/s10342-022-01462-8

ORIGINAL PAPER

Multi-year, post-harvesting impact assessment in a neotropical secondary Atlantic Forest

Pedro Caldas Britto[1] · **Dirk Jaeger**[1] · **Stephan Hoffmann**[2] · **Renato Cesar Gonçalves Robert**[3] · **Alexander Christian Vibrans**[4] · **Alfredo Celso Fantini**[5]

Received: 17 October 2020 / Revised: 29 April 2022 / Accepted: 9 May 2022 / Published online: 24 June 2022

Abstract

Subject to overexploitation in the past centuries, the Atlantic Forest is subject to very rigorous protection rules. However, the law is a controversial issue since landowners are not compensated for the limited choice of land use possibilities. We believe that, alternatively to a general timber harvest ban, sustainable forest management of the Atlantic Forest has the potential to generate income for the landowners while sustaining important ecological functions of the forest. Such choice would require better understanding of the potential effects of timber harvesting on the forest ecosystem and on species composition and succession over time. In this context, we assessed the harvesting impact of a conventional harvesting method (CM) and compared it to an alternative harvesting method (AM) in three different stands (stands A, B and C) of a secondary forest fragment in southern Brazil. Results from three comprehensive forest inventories over a period of two years were used to assess the timber harvesting impact. Measurements of species composition (i.e., number of species, life form, ecological group), forest structure (i.e., density, basal area, DBH, volume) and saplings density formed the basis of the impact assessment. The inventories were carried out before, immediately after and two years after harvesting. Intensities of damage on remnant trees immediately after harvesting and two years after harvesting were also measured. Before harvesting, a total of 114 tree species (trees, tree fern and palm tree) belonging to 49 families were identified in the study site's three research stands. Palm trees and secondary species, such as *Euterpe edulis*, represented the majority of recruited individuals ($DBH \geq 5$ cm) two years after harvesting. However, new saplings ($DBH \leq 5$ cm) after two years were mainly pioneer woody tree species, such as *Cecropia glaziovii* and *Schizolobium parahyba*. On average, AM reduced damage to saplings by 5%. Most of the damages caused by CM were moderate to severe, while AM caused light to moderate damages. Binary logistic regression indicated dependency of the mortality rates on the independent variables "stand, stem and leaning damages." On the other hand, the recovery rates of damaged trees were dependent on crown, stem and leaning damages. Therefore, two years after harvesting a higher mortality rate of low-dimensional trees was observed in stands with high density of smaller trees and high density of improvement felling. Although crown damages were not related to mortality rates, high intensity of crown damages reduced recovery rates over time.

Keywords Reduced impact logging · Logging damages · Mortality and recovery rates · Tractor winch · Snatch block · Skidding cone

Introduction

As one of the most threatened Biomes in South America, the Atlantic Forest is currently subject to a very controversial debate on conservation and management. Sustainable forest management in the Biome has the potential to actively support the process of ecosystem recovery and rehabilitation and, at the same time, generate income opportunities for landowners (Britto et al. 2019; Fantini et al. 2019). One component of successful forest management is a harvesting

---

Communicated by Eric R. Labelle.

✉ Pedro Caldas Britto
pedro.britto@gmx.de

Extended author information available on the last page of the article

method adapted to secondary forests to lower harvesting impact, which implies lower damages to residual trees and forest soils as well as a lower impact on biodiversity and ecosystem services.

The Brazilian Atlantic Forest is exceptionally rich in biodiversity and originally covered around 150 million hectares (Metzger 2009). Housing two-thirds of Brazil's population (Jacobsen 2003), it is one of the most threatened Biomes in Brazil (Trevisan et al. 2016). After centuries of intensive exploitation and conversion to other land uses, the forest area was reduced to only 12% of its original extension (Ribeiro et al. 2009). Today, the remnant forest is highly fragmented, representing small patches (less than 50 ha in size), owned by private landowners. In Santa Catarina State, second-growth forest represents 95% of the remaining forest cover (Vibrans et al. 2012) with a significant timber volume from fast-growing species at ages as young as 30–40 years (Zambiazi et al. 2021). These forests were regenerated on abandoned land previously used for crop production or pasture cultivation (Fantini et al. 2019).

Aiming to protect the remnant forest cover from deforestation and degradation, the Brazilian government established a very strict protection for the Atlantic Forest Biome resulting in land use regulations issued in 1981 (law number 6938/81: Environment National Policy), 1993 (federal decree number 750/93) and 2006 (law number 11,428/06: Mata Atlantica Law) (Kengen 2019). Currently, irrespective of the size, all forest fragments are protected, and land use possibilities are very limited, with few exceptions in urban areas. Endorsement of such policy, however, has been controversial as it turns conservation and management conflicting goals. According to Karsten et al. (2013), strict guidelines on sustainable forest management are no guarantee for preserving species composition in tropical forests. Numerous researchers have argued that policy incentives fostering sustainable management of secondary forests may generate income opportunities for the landowners, favoring local development and, at the same time, maintaining core ecosystems services provided by this forest. Therefore, it would be more effective to conserve and possibly even expand the forest cover (Alarcon et al. 2011; Britto et al. 2019, 2017; Fantini et al. 2019; Santos et al. 2019; Silva et al. 2018; Trevisan et al. 2016; Zambiazi et al. 2021). Research analyzing alternative forest management strategies is fundamental for knowledge-based decision making with respect to potential utilization of native tree species from the Atlantic Forest, through responsible and regulated timber harvesting (Alarcon et al. 2011).

Within this context, a research study site was set in the municipality of Guaramirim, Santa Catarina State, southern Brazil, within the Atlantic Forest Biome, where various alternative forest management regimes for sustainable forest management, including timber utilization, are tested and evaluated (Britto et al. 2017, 2019). The present study aimed at better understanding the potential impacts of timber harvesting operations within sustainable management strategies for the Atlantic Forest. The Institute for the Environment of Santa Catarina (IMA) is one of the partners in this study and granted an exemption of the general harvesting ban to enable a long-term research project investigating varying timber harvesting intensities in single-tree operations and possible impacts on residual stands.

Although any harvesting operation may cause damage to the residual stand, its intensity can be significantly reduced by applying harvesting systems that are appropriate and adapted to local forest conditions (Britto et al. 2017; Darrigo et al. 2016). Furthermore, methods of reduced impact logging (RIL) might not only reduce impacts caused by tree felling and extraction, but also provide more favorable conditions for forest recovery over time (Dionisio et al. 2017, 2018; Putz et al. 2008). Forest management also may lead to changes in the species composition (Nagaike and Hayashi 2004), which may help to improve the forest recovery and the sustainable use of forest resources. However, in order to take advantage of this possibility, it is fundamental to understand how the forests respond to human disturbances at multiple levels including the retained biodiversity (Joly et al. 2014) and the variation in species compositions formed by different number of species, life forms and ecological groups.

The present study is part of a comprehensive research currently under development in the Atlantic Forest biome. Previous studies in the same research area have already investigated the economic potential of secondary Atlantic Forests (Fantini et al. 2019; Fantini and Siminski 2017; Trevisan et al. 2016; Zambiazi et al. 2021), volumetric models and aboveground biomass (Oliveira et al. 2018; Uller et al. 2021, 2019); regeneration of woody species (Piazza et al. 2017); as well as productivity and costs of timber harvesting operations (Britto et al. 2017), harvesting impacts caused by forest management (Britto et al. 2019; Bulfe et al. 2009; Ruy et al. 2014; Silva et al. 2018) and impacts on canopy architecture after logging (Silva & Vibrans 2019).

Other studies have evaluated the impact of forest operations on species diversity and composition (Gourlet-Fleury et al. 2013; Tavankar and Boynad 2015, Bennett and Adams, 2004; Uuttera et al. 1997; Canetti et al. 2021), on the regeneration of saplings (Gyamfi et al. 2014; Darrigo et al. 2016; Karsten et al. 2013) and the recovery and mortality rates after reduced impact logging in tropical forests (Pena-Claros et al. 2008; Dionisio et al. 2017, 2018). However, studies to assess the timber harvesting impacts of different harvesting methods on the species composition and recovery rates in the Atlantic Forest are still missing.

The goal of the present study was, therefore, to contribute to fill the current knowledge gap on suitable harvesting methods and forest utilization in secondary Atlantic Forests by evaluating the impacts of timber harvesting and extraction on species composition and stand structure up to two years after the harvesting operation. We studied the impacts of two different harvesting methods (alternative: AM and conventional: CM) applied to three secondary forest stands with different structures and terrain slopes were assessed, in order to answer the following research questions: (a) How do the timber harvesting methods affect the species composition with respect to number of species, different life forms and ecological groups, over a period of two years?; (b) How does the timber harvesting affect the stand's basal area, diameter distribution and height classes?; (c) How do timber harvesting methods affect saplings density over a period of two years?; and d) How does the timber harvesting affect the recovery rates of damaged trees after two years?

Materials and methods

Study site

The Atlantic Forest Biome has a wide longitudinal range. It is distributed along 29 degrees extending from 3° S to 31° S along tropical and subtropical regions (Ribeiro et al., 2009) with great variations in elevation, ranging from sea level to 2,892 m a.s.l. (Pinto and Brito, 2003). The wide longitudinal range (from 35° W to 60° W) is also a vital aspect contributing to the manifold forest composition since rainfall intensity decreases away from the coasts. Due to this wide longitudinal range, the Atlantic Forest is not homogeneously distributed (Silva and Casteli, 2002) and it is composed of numerous vegetation types (Pinto and Brito, 2002). The present study was performed in the forest formations classified as evergreen rainforests (ERF), which is one of the most common forest formations in the Atlantic Forest Biome (Vibrans et al. 2013). The ERF is characterized by the presence of large- and medium-sized trees and abundant epiphytes. It extends along the Atlantic coast from the northeast to the extreme south of Brazil. Its occurrence is linked to the hot and humid tropical climate, without dry season, with well-distributed rainfall throughout the year. Over 500 tree species may be found in the evergreen rainforests (Lingner et al. 2015). The secondary forest of the region forms a mosaic of small patches with particular site conditions, as well as the forest composition and structure. These forests are characterized by a high heterogeneity among stands, steep slopes, high tree density and trees with low-dimensional stems (Britto et al. 2019).

The research area is located at the municipality of Guaramirim, state of Santa Catarina, southern Brazil (26°32,010″ S and 49°02,038″ W, approximately). The study area encompassed 42 ha covered by a 36-year-old second-growth forest, which regenerated after the abandonment of plots cultivated under swidden agriculture (Fantini et al. 2019). Forest soils of the region predominantly consist of Red Yellow Podzolic with low natural fertility. The climate in the region is subtropical humid with a hot summer and no dry season. The local mean annual temperature is 20.9 °C, and the mean annual precipitation is 1613 mm (Alvares et al. 2013).

During a previous investigation (Britto et al. 2019), permanent research plots in three different stands (A, B and C) of the research area were established. Stand A was characterized by commercial trees of bigger dimensions compared with the other two sites, located on steep terrain (≈ 50% slope), and similar to old growth forest regarding species composition and tree dimensions. Stand B was composed of smaller trees and a few bigger commercial trees, located on less steep terrain (≈ 10–25% slope). Stand C, represented a young stand (less than 20 years old) with a high density of smaller trees, one dominant tree species (*Clusia criuva*), and located on a rather flat terrain (≈ 5–10% slope). In order to compare the harvesting methods, in each stand two blocks of 0.16 ha each were established, with each block further subdivided into 16 plots of 10 m × 10 m each. Despite the relatively small area of each block and its respective plots, high heterogeneity, a typical characteristic of secondary forests in the ERF region, was observed between plots (Britto et al. 2019). Although we found, besides trees, some non-woody tree-like species as arborescent ferns (*Cyathea sp.*) and small- to medium-sized palms (*Euterpe edulis*), from now on we use the general term "tree" or "tree species" when referring to the individuals with diameter at breast height (DBH) above 5 cm.

Stand structural inventory

We performed a full pre-harvesting inventory recording tree species, DBH, tree height and tree location (Cartesian X- and Y-coordinates), of all individuals above 5 cm DBH. We also marked and numbered every measured tree with an aluminum tag, allowing for individual identification during the intended multi-year post-harvesting monitoring of the plots. A first post-harvesting inventory was performed immediately after harvesting, and a second post-harvesting inventory was performed two years after harvesting. Stem volumes of individual trees were calculated following a volumetric model proposed by Oliveira et al. (2018). The recorded species were further classified by life form groups (i.e., palm tree, tree, tree fern) and into ecological groups (i.e., pioneer, secondary, climax species) according to Reitz (1965) and Swaine and Whitmore (1988) and into seed dispersal syndromes as per Pijl (1969). For the purpose of this research, pioneer species were considered fast growing, light demanding, shade intolerant and with seed banks experiencing dormancy. Secondary species were considered shade tolerant as seedlings, gap specialists exhibiting intermediate growth rhythm, with seedling banks frequent, but dormancy rare. Climax species were considered slow growing, predominantly shade demanding as seedlings and shade demanding or shade tolerant as juveniles or adults, with seedling banks present and dormancy absent. Additionally, we identified rare species based on Oliveira et al. (2019) and commercially important tree species based on Fantini et al. (2019).

Saplings were assessed by measuring individuals with a minimum height of 1.3 m and a DBH below 5 cm (Piazza et al. 2017). Saplings were recorded in four 2 m × 10 m sub-plots equidistantly distributed within each plot within each of the larger of 10 m × 10 m. These sub-plots were installed perpendicular to the planned winching lines. The saplings were identified to the species level and were measured for DBH (when possible) and height. All saplings were also marked with an aluminum tag for easy future identification.

Harvesting

Timber harvesting was performed in all three stands targeting a harvesting intensity of 40% basal area reduction, similar to that in Britto et al. (2017) and Silva et al. (2018). The harvesting operation included felling of both commercial and non-commercial trees. Commercial felling focused on mature trees of species of economic value to generate maximum revenue for the landowner. Non-commercial felling targeted small trees of low quality or economic value for stand improvement (Britto et al. 2019). While all commercial logs were extracted from the stand, most of the stems resulting from improvement felling remained inside the stands except for those at close distance to a forest road, which were used for firewood (Britto et al. 2017).

For timber harvesting, the tree length method was applied: Trees were felled, delimbed and bucked inside the stand using a chainsaw; the log was then extracted with a winch-fitted tractor, positioned outside of the stand, on a forest road. A co-worker assisted the tractor operator, pulling out the cable from the winch to the log's location inside the stand (Britto et al. 2017).

We compared a local "conventional method" (CM) and an "alternative method" (AM) of harvesting. Both harvesting methods were considered as reduced impact logging (RIL). However, the CM was conducted by the forest owner, which represented a locally and widely used harvesting method applied by people with no formal training, but with extensive practical experience in tree felling. In contrast, the AM was performed by a contracted professional chainsaw operator, experienced in RIL techniques in the Amazon region. He executed the tree felling with a Stihl® chainsaw (model 661), and the log was extracted with a standard TAJFUN® winch (model EGV 85 AHK), fitted to a 4 × 4 tractor. In addition, AM used a Portable Winch® skidding cone and a TAJFUN® snatch block (Britto et al. 2019) to extract the log. The CM included the use of a Stihl® chainsaw (model 251) and extracting the logs with a standard 2 × 2 farm tractor, fitted with the locally common TMO Caçador® winch (model 33 T). The performance of both harvesting methods was analyzed by Britto et al. (2017).

Tree damage assessment

Damages to remnant trees caused during timber harvesting were analyzed through two full inventories: (a) immediately after the harvesting operation and (b) two years after harvesting. Stand damages to remnant trees (DBH above 5 cm) caused by tree felling and extraction were assessed by visual inspection, and recording undamaged, damaged or dead trees (Britto et al. 2019). Damaged trees were categorized and rated according to damage severity classes (minor, moderate and severe) in damage categories related to the crown, bole and leaning, following Silva et al. (2018) (Table 1).

The damage intensity and rating value of each tree immediately after harvesting was compared to the damage intensity of the same tree two years after harvesting and classified into: (a) completely recovered tree; (b) partially recovered tree; (c) same damage; and (d) dead tree (Table 2).

Analytical methods

As mentioned before, the analytical design of the present study was based on previous investigation in the same research area (Britto et al. 2017, 2019). Permanent research plots in three different stands (A, B and C) were established. To compare the harvesting methods, in each stand

Table 1 Classification criteria for harvesting damage to residual trees in a secondary Atlantic Forest adapted from Silva et al. (2018)

Category of damage	Intensity of damage					
	Minor	Rating value	Moderate	Rating value	Severe	Rating value
Crown damage	X < 1/3 of crown	*1*	1/3 < X < 2/3 of crown	*2*	X > 2/3 of crown	*3*
Bole damage	Bark damage	*1*	Superficial wood damage (cambial tissue)	*2*	Deep wood damage (sub cambial tissue)	*3*
Tree leaning	Slight leaning	*1*	Partially uprooted	*2*	Fully uprooted	*3*

Table 2 Classification criteria for recovery and mortality rate two years after harvesting

Rating value	Recovery classes	Description
1	Completely recovered tree	Trees that presented no damage after two years
2	Partially recovered tree	Trees that presented a reduction in the damage intensity rates
3	Same damage	Trees with the same damage intensity rates
4	Dead tree	Trees that died off or were not found two years after harvesting

we established two blocks of 0.16 ha each, and each block was further subdivided into 16 plots of 10 m × 10 m each.

Initially, homogeneity of the three stands was compared with respect to structural characteristics (nonparametric Whitney U Test, $p < 0.05$), which included stand density (number of trees per area), tree DBH, tree height, stand basal area (of trees ≥ 5 cm DBH) and stocking volume. Additionally, nonparametric tests (Kruskal–Wallis and Friedman) were applied to compare harvesting methods within the stands, with respect to tree density, basal area and volume. Comparison of harvesting methods was done considering only inventory data from the same inventory period and the same tree life form group or ecological group.

Differences among the three sequential inventories were tested by using the t-test for repeated measures, with respect to (a) tree density for each life form and ecological group; (b) tree density for each DBH and height classes; and (c) saplings density. This analysis considered only the differences among three inventories which were performed at different times within the same research plot. All the statistical analyses were performed with the software IBM SPSS Statistics, version 27 (IBM Corp., Armonk, NY, USA).

Damage to remnant trees was assessed through binary logistic regression (Hosmer and Lemeshow test) aiming to verify the correlation between independent variables such as harvesting methods (AM and CM), stand (A, B, C) and damage intensities immediately after harvesting (minor 1; moderate 2; severe 3) with the mortality and recovery rate two years after harvesting. Dummy variables (0, 1) were attributed for the recovery and mortality rates. The model was generated with the software IBM SPSS Statistics, version 27.

Results

Forest structure

Considering all inventoried trees (about 2,000), in the three sampled stands (about 1 ha in total) most of the species (59%) were represented by no more than five individuals in the three research stands (Fig. 1). A total of 114 tree species (trees, tree ferns and palm trees) belonging to 49 families were identified before harvesting, which represented nearly 20% of the 577 tree species occurring in the evergreen rainforests (ERF) as described by Lingner et al. (2015). The most abundant species recorded before harvesting were: C*lusia criuva* (10%), *Cyathea* sp. (10%), *Euterpe edulis* (8%) and the important commercial tree *Hyeronima alchorneoides* (8%). We also recorded other commercially important woody tree species, such as *Cabralea canjerana, Cedrela fissilis, Citharexylum myrianthum, Cupania vernalis, Matayba intermedia, Miconia cabucu, Trichilia lepidota, Virola bicuhyba* and *Xylopia brasiliensis,* as well as some rare species, such as *Maytenus ilicifolia*, *Trichilia pallens* and *Eugenia burkartiana*.

We observed a loss of seven species immediately after harvesting and another five species two years after harvesting. Conversely, three new species were recorded in the inventory two years after harvesting.

Despite the small size of the research area, we observed heterogeneity between the three stands. While stand A, on steep terrain, showed higher number of species and diversity at both plots, stand C with its dense stand, on a rather flat terrain, showed only 60% of the number of species observed in stand A. Even after harvesting, stand A and B presented a higher number of species and diversity than that observed in stand C before harvesting, irrespective of the applied harvesting method. Moreover, in all three stands a reduction in the total number of species between the pre-harvesting inventory and the first post-harvesting inventory was observed. Ignoring the lower number of species of stand C compared to stands A and B before timber harvesting, stand C was the only one showing an increase in the number of species between the first and the second post-harvesting inventory (Table 3).

In relation to the life form groups, most of the species (110 species) were classified as woody tree species, followed by palm trees (two species) and tree ferns (two species), whereas only 4% of all trees species remained unidentified. Throughout all plots, woody trees showed the highest densities, followed by tree ferns. These densities differed significantly for all recorded life forms between the inventories carried out immediately after harvesting and two years after harvesting.

As intended by the timber harvesting operation, the highest changes and density reductions occurred between the pre-harvesting inventory and the first post-harvesting inventory (immediately after harvesting) irrespective of the harvesting method employed. Among the life forms, trees (here

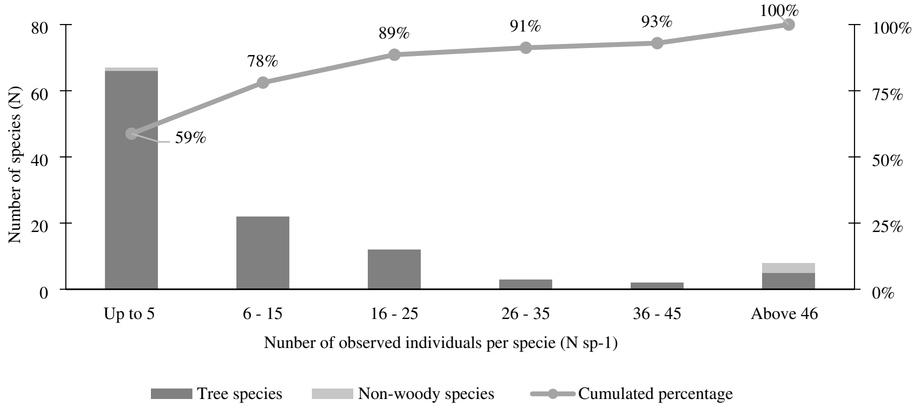


Fig. 1 Number of species per number of observed individuals per species and the accumulated total number of species

Table 3 Total number of species (N) per 0.32 ha inventoried stand, of a late secondary forest selectively harvested across stands, irrespective of harvesting method

Stand	a. All tree species			b. Only woody tree species		
	Pre	After	2 years	Pre	After	2 years
	Number of species (N)			Number of species (N)		
A	88	79	79	84	75	75
B	69	64	63	65	60	59
C	54	47	47	49	42	43

*Pre = Pre-harvesting; After = Immediately after harvesting; 2 years = Two years after harvesting. Each stand was 0.32 ha

referring to woody tree species) showed the highest level of density loss immediately after harvesting. However, it was noticed a clear trend showing a continuous decrease in tree density among all life form groups until two years after harvesting, with palm trees, in particular *Euterpe edulis*, being the only exception (Fig. 2).

Despite their low density before harvesting, palm trees presented higher density in the second post-harvesting inventory, two years after harvesting. Compared to trees and tree ferns, palm trees represented a large proportion of recruited individuals (DBH > 5 cm) in the second post-harvesting inventory for both harvesting methods (Fig. 3).

The majority of tree species registered were classified as pioneer (31), secondary (47) or climax (27). Nine species were classified only to the genus level and were not assigned to an ecological group, representing 16% of the total number of trees. Secondary species included shade-tolerant species and made up the largest component of the forest structure, followed by climax and pioneer species. Trees of all recorded ecological groups showed a significant reduction in densities between pre- and first post-harvesting inventories (Fig. 4).

However, there was a significant reduction in density between the first and the second post-harvesting inventories for climax and unidentified species. The density of pioneer species also decreased two years after harvesting. On the other hand, secondary species showed a slight increment two years after harvesting. Secondary species constituted the majority of recruited trees recorded in the second post-harvesting inventory (Fig. 5).

The reduction in the number of trees between pre- and first post-harvesting inventories (Figs. 2 and 4) was related to tree DBH. The greatest reduction occurred in the lowest DBH classes (Fig. 6). However, when comparing the first and the second post-harvest inventories, there was a further loss of small trees, while trees with DBH greater than or equal to 25 cm showed an increased density, resulting in a significant increase in basal area and volume over the two-year measuring interval.

When plotted against tree height classes, tree density at all three inventory periods pointed out a reduction in tree density mainly in the lower height classes (up to 10 m height) (Fig. 7). However, for tree species in higher height classes (above 14.7 m height), significant increases in tree density between first and second post-harvesting inventory were noticed.

Although a statistically significant difference between harvesting methods was not found, in general, a reduction in tree density, basal area and volume after harvesting was observed. Tree densities still decreased two years after harvesting for most of the stands. However, basal area and stocking volumes increased slightly from the first

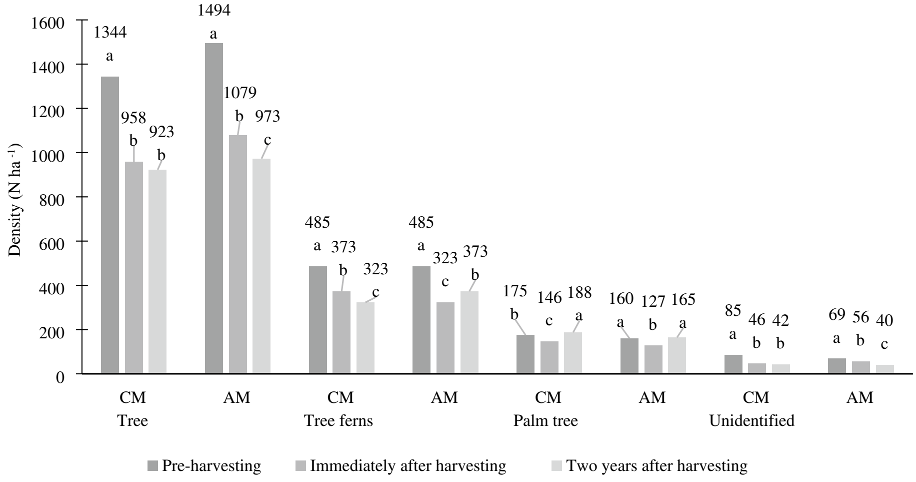


Fig. 2 Tree density (N ha.$^{-1}$) of different life forms in a secondary forest selectively harvested under conventional (CM) and alternative (AM) harvesting methods, inventoried over three different periods. Different lowercase letters within the same life form group indicate significant differences between periods of the same harvesting method. Comparisons between harvesting methods are statistically nonsignificant

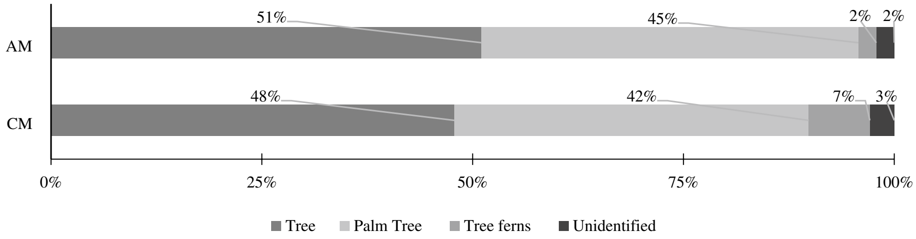


Fig. 3 Proportion of life form groups of recruited t individuals in a secondary forest harvested under conventional (CM) and alternative (AM) harvesting methods, two years after the harvesting

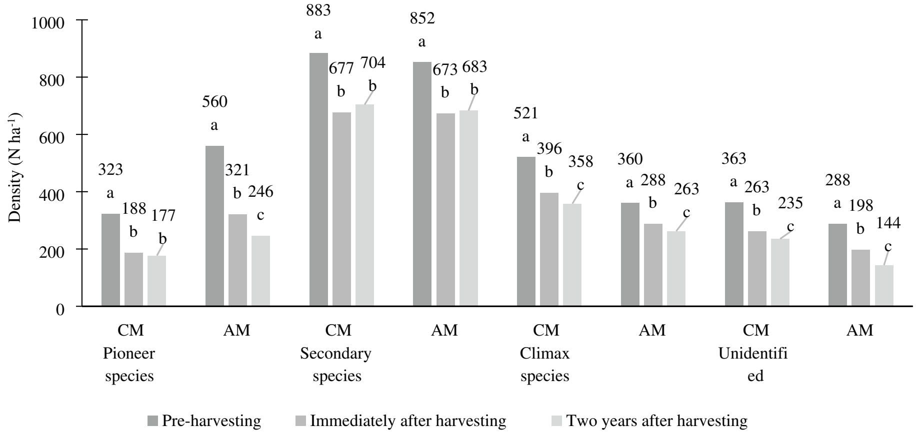


Fig. 4 Tree density of different ecological groups in a secondary forest selectively harvested under conventional (CM) and alternative (AM) harvesting methods, inventoried over three different periods. Different lowercase letters in the same ecological group indicate significant differences between periods for the same harvesting method. Comparisons between harvesting methods are statistically nonsignificant

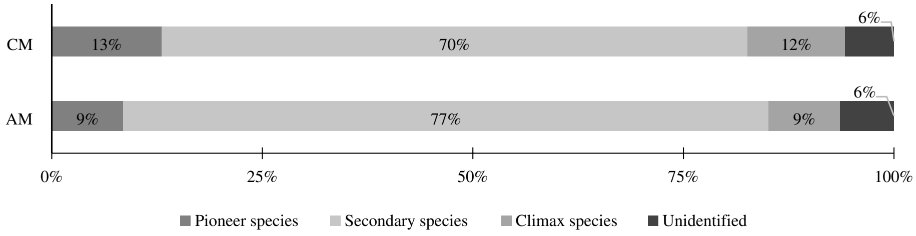


Fig. 5 Proportion of ecological groups of recruited trees in a secondary forest harvested under conventional (CM) and alternative (AM) harvesting methods, two years after harvesting (all trees > 5 cm DBH)

Fig. 6 Tree density per DBH class in a secondary forest harvested under conventional (CM) and alternative (AM) harvesting methods, inventoried over three different periods (tree life form groups other than trees were excluded). Different lowercase letters in the same DBH class indicate significant differences between periods for the same harvesting method. Comparisons between harvesting methods are statistically nonsignificant

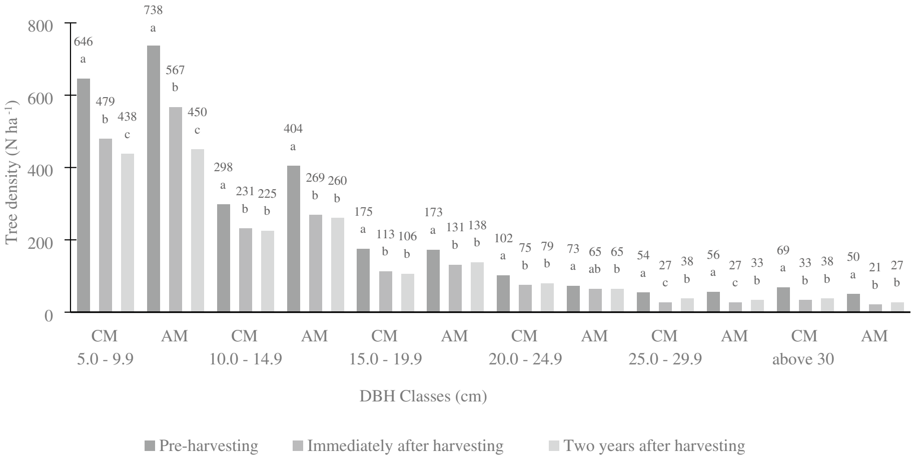
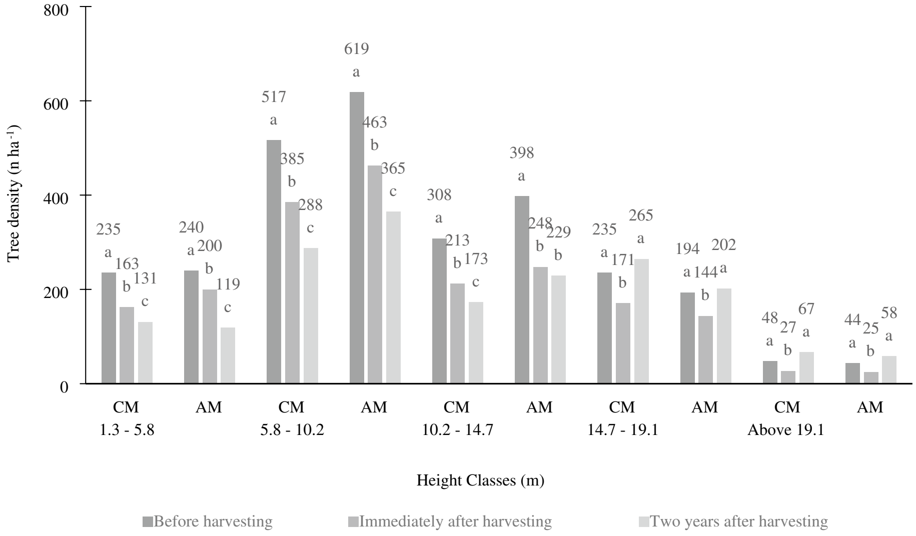


Fig. 7 Tree density per class of tree height in a secondary forest harvested under conventional (CM) and alternative (AM) harvesting methods, inventoried over three different periods. Only trees above 5 cm DBH were included. Different lowercase letters in the same height class indicate significant differences between periods for the same harvesting method. Comparisons between harvesting methods are statistically nonsignificant



post-harvesting to two years after harvesting (Table 4), suggesting that most density loss was caused by loss of smaller trees and that remnant trees showed higher growing rates after harvesting.

Regeneration

The density of regenerants (saplings below 5 cm DBH and above 1.3 m height) ranged widely from 4,812 saplings ha^{-1} (CM stand A) to 11,593 saplings ha^{-1} (CM stand C) before harvesting. In all three stands, a significant reduction in saplings density was observed immediately after harvesting, irrespective of the harvesting method. On average, stands harvested under CM showed 5% more in damaged saplings compared with stands harvested under AM. However, two years after harvesting, a significant recovery of the saplings density was observed (Table 5).

Most of the new saplings were woody tree species (91% in the stands harvested under CM and AM), followed by palm trees (5% and 4% in stands harvested under CM and AM, respectively). No tree ferns were recorded among new regenerants two years after harvesting (Fig. 8).

Regardless of the harvesting method, two years after harvesting 43% of all saplings were new trees not recorded before, of which half belonged to pioneer species (almost 20%), followed by secondary species (Fig. 9).

Damaged trees

A total of 429 trees were damaged during the harvesting operation in all stands, 51% and 49% in stands harvested under CM and AM, respectively. Crown and stem damages were the predominant damage category, irrespective of harvesting method. We found that 32% of all damaged trees suffered only crown damages, while another 33% of damaged trees were impacted only by stem damages or suffered leaning (2%) damages. Among all damaged trees, 31% suffered

Table 4 Tree density, basal area and stocking volume of a secondary forest harvested under conventional (CM) and alternative (AM) harvesting methods

Harvesting method	Stand	a. All trees			b. Only woody species			c. Commercial woody species		
		Pre	After	2 years	Pre	After	2 years	Pre	After	2 years
		Density (N ha.$^{-1}$)								
CM	A	2,293 a	1,662 b	1,506 b	1,100 a	806 b	750 b	456 a	331 b	306 b
	B	1,968 a	1,625 b	1,550 b	1,356 a	1,093 b	1,050 b	525 a	431 b	412 b
	C	2,006 a	1,281 b	1,368 b	1,575 a	975 b	968 b	843 a	575 b	537 b
AM	A	1,975 a	1,562 b	1,456 b	1,200 a	1,037 b	981 b	550 a	443 b	443 b
	B	1,737 a	1,343 b	1,362 b	1,175 a	918 b	906 b	568 a	443 b	431 b
	C	2,468 a	1,531 a	1,187 a	2,106 a	1,281 b	1,031 b	768 a	625 b	550 b
		Basal area (m^2 ha.$^{-1}$)								
CM	A	41.7 a	26.1 b	26.0 b	29.0 a	17.6 b	18.4 b	18.7 a	11.1 b	11.2 b
	B	26.3 a	18.3 b	19.5 b	21.6 a	14.9 b	15.6 b	15.4 a	10.3 b	10.6 b
	C	29.0 a	14.7 b	16.0 b	25.8 a	12.5 b	13.1 b	14.7 a	8.8 b	9.3 b
AM	A	34.4 a	23.6 b	23.7 b	26.5 a	18.9 b	19.1 b	18.7 a	12.5 b	12.9 b
	B	31.1 a	20.7 b	21.9 b	25.5 a	16.0 b	16.7 b	17.9 a	11.2 b	12.0 b
	C	31.5 a	16.6 b	14.8 b	28.3 a	14.0 b	12.7 b	10.8 a	9.1 b	8.8 b
		Stocking volume (m^3 ha.$^{-1}$)								
CM	A	317 a	188 b	208 b	232 a	133 b	156 b	151 a	89 b	100 b
	B	199 a	134 b	145 b	172 a	116 b	123 b	134 a	90 b	92 b
	C	195 a	104 b	117 b	179 a	92 b	102 b	109 a	69 b	76 b
AM	A	246 a	168 b	186 b	196 a	139 b	155 ab	137 a	91 a	111 ab
	B	215 a	145 a	171 a	184 a	119 a	137 a	136 a	89 a	104 a
	C	204 a	111 b	104 b	187 a	95 b	90 b	76 a	64 b	65 ab

Pre = Pre-harvesting; After = Immediately after harvesting; 2 years = Two years after harvesting. Different lowercase letters in the same line indicate significant differences between different periods for the same stand and harvesting method. Comparisons between harvesting methods are statistically nonsignificant

more than one damage type. Two years after the timber harvesting operation, almost 20% of all damaged trees were completely lost (22% in CM stands and 18% in AM stands) and another 30% did not show any damage (recovered), irrespective of the harvesting method (Table 6).

A reduction in damage intensity in all crown damaged categories in most of the surviving individuals was observed. While moderate crown damages were predominant in CM stands inventoried immediately after harvesting, 30% of the trees recovered completely within the subsequent two years. In AM stands, where light crown damages were predominant immediately after harvesting, almost 40% of the trees recovered completely within two years. However, most of the severely damaged individuals in CM stands were found dead two years after the timber harvesting operation, while most of the severe crown damages due to AM harvesting showed slight recovery and were downgraded to moderate damage (Table 7).

With respect to stem damages, light damages were predominant in the first post-harvesting inventory, irrespective of harvesting method. Two years after harvesting 44% of trees with light stem damages recovered completely in all stands, whereas trees with moderate to severe stem damages showed clearly lower recovery rates and higher mortality for stands in CM and AM stands (Table 8).

Only 3% of the trees were damaged during timber harvesting by being pushed into leaning positions. Most of the leaning trees showed only light damages immediately after harvesting. However, the recovery rate of leaning individuals was very low within the two years after harvesting; most of them either remained in the same damage category or died off irrespective of harvesting method (Table 9).

Mortality rates model presented significant correlation ($p < 0.05$) (Hosmer and Lemeshow test), for the independent variables "stands," "stem damage intensity" and "leaning damage intensity". Positive correlation implies that higher stem and leaning damages caused a higher mortality rate. Understandably, stem and leaning damages presented a negative effect on the recovery rates. Although crown damages

Table 5 Density of saplings (N ha.$^{-1}$) in a secondary forest harvested under conventional (CM) and alternative (AM) harvesting methods, inventoried in three different periods

Harvesting-method	Stand	a. All tree species					b. Only woody species				
		Pre (N ha^{-1})	After (N ha^{-1})	(%)	2 years (N ha^{-1})	(%)	Pre (N ha^{-1})	After (N ha^{-1})	(%)	2 years (N ha^{-1})	(%)
CM	A	4,800 a	3,200 b	67%	5,500 a	115%	3,100 b	2,250 c	73%	4,800 a	155%
	B	6,150 a	4,050 c	66%	6,000 b	98%	5,400 a	3,650 b	68%	5,400 a	100%
	C	11,600 a	7,950 b	68%	9,200 a	79%	9,900 a	6,950 c	70%	8,150 b	82%
AM	A	7,150 a	5,300 b	74%	7,450 a	104%	4,650 b	3,500 c	75%	6,100 a	131%
	B	6,050 a	4,300 b	71%	5,700 a	94%	4,900 a	3,500 b	71%	5,000 a	102%
	C	7,900 a	5,700 c	72%	6,450 b	(2%	7,550 a	5,400 c	72%	5,950 b	79%

Pre = Pre-harvesting; After = Immediately after harvesting; 2 years = Two years after harvesting. Different lowercase letters in the same line indicate significant differences between different inventoried periods for the same harvesting method and stand. The percentages indicate the proportion of remnant regenerants compared to the number of regenerants before harvesting. Comparisons between harvesting methods are statistically nonsignificant

was not strongly correlated with the mortality rates, it clearly negatively influenced the recovery rates (Table 10).

Discussion

Despite the relatively small research site (42 ha), we found a high heterogeneity among the three examined stands with respect to species composition and horizontal and vertical structure. For Britto et al. (2019), this high heterogeneity associated with the small number of replications proved to be a challenge for the designing research trials and the statistical comparison between harvesting methods. However, it is important to mention that the remnant secondary Atlantic Forest is a mosaic of several and small forest patches (Fantini and Siminski 2017; Lingner et al. 2015; Ribeiro et al. 2009). Therefore, the environmental conditions of the site studied are typical conditions of the Atlantic Forest, allowing to scale up the results to other similar forests of this Biome.

Stand A, located in a steep slope and with low accessibility, showed a higher number of species compared to stand C, located on flat terrain near to a landing area. This result reinforced the perception that most of the preserved forest fragments in Atlantic Forest are located in sites where steep terrain made other land uses particularly difficult (Ribeiro et al. 2009; Silva et al. 2007). Timber harvesting in stand C with a high density of small trees resulted in relatively high numbers of felled trees and particular focus on improvement felling removing non-commercial trees and small trees or shrub species (Britto et al. 2019). While this treatment did not result in increased number of species and diversity two years after harvesting, a significant loss of number of species was not observed.

As expected, timber harvesting resulted in significant reductions of tree density, basal area and volume of trees and other life forms, irrespective of the harvesting method used (Table 3). Timber harvesting also caused the loss of 12 species in the research plots. However, we should look at this result with caution because it was likely inflated by the combination of low density of individuals per species and the small area of each plot inventoried. None of the species missing after harvesting were classified as threatened or rare species (Oliveira et al. 2019) which reinforce this argument.

A forest is expected to regenerate after harvesting, raising the density of trees (Magnusson et al. 1999). However, all three stands here studied showed lower tree density two years after harvesting (Table 3), possibly reflecting a negative balance between mortality and regeneration. A highest mortality rate in the first years after harvesting was also observed by Dionisio et al. (2017) and Dionisio et al. (2018) in studies of reduced impact logging in the Amazonian tropical forest. The same authors also observed a

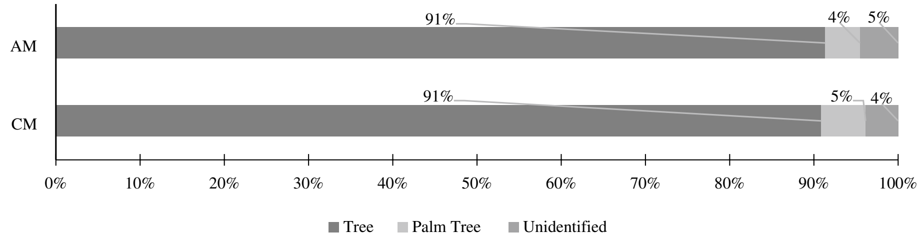


Fig. 8 Proportion of new saplings classified by life form group in a secondary forest harvested under conventional (CM) and alternative (AM) harvesting methods, two years after harvesting

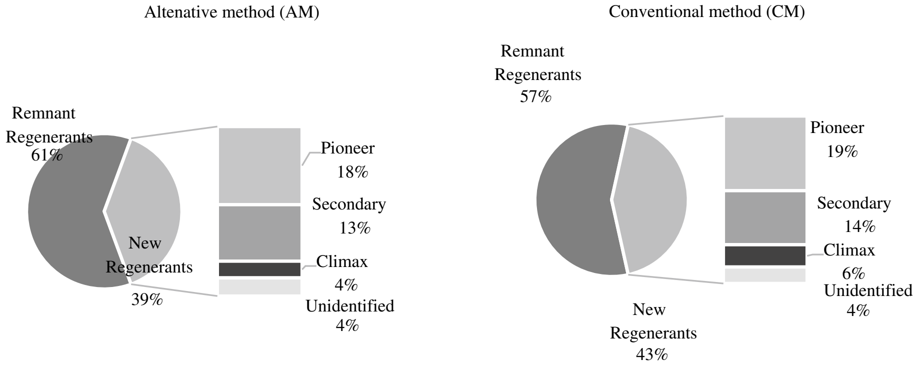


Fig. 9 Proportion of all saplings in the inventory two years after harvesting with applied harvesting methods (AM) and (CM). New regenerants were classified by ecological groups

reduction in the mortality rate only after the seventh year after timber harvesting. Most of the lost individuals were of smaller dimensions, with low DBH (Britto et al. 2019; Silva et al. 2018). The impact of single-tree harvesting along with changes of the forest structure in the forest here studied, such as a sudden exposure of trees to full light, may explain to the continuation of tree loss until two years after harvesting. In contrast, remnant trees higher than 25 cm DBH showed significant growth since the harvesting two years earlier, as revealed by increased number of individuals with higher DBH classes (Fig. 6), larger mean DBH (Fig. 5) and slightly larger basal areas and stocking volumes of the test plots. A similar pattern was also observed by Dionisio et al. (2018) in the Amazonian Forest. Furthermore, this result suggested that single-tree harvesting favors growing conditions for trees of higher DBH classes (usually commercial trees), with likely positive effects on shortening of felling cycles, as anticipated by Fantini et al. (2019). Zambiazi et al. (2021) also pointed out the dominance of secondary Atlantic Forest by fast-growing species and wood-producing species capable of producing timber quality after 20 years of succession and yet maintaining the important biodiversity reservoir and other ecosystem services. One of the benefits of timber harvesting may be to promote the establishment of fast-growing timber species (Duah-Gyamfi et al. 2014).

There were no significant differences between the two applied harvesting methods with respect to impact on life form categories. As intended by the timber harvesting operation, the highest changes in densities occurred between the pre-harvesting inventory and the first post-harvesting inventory for woody tree species, irrespective to the harvesting method. This was expected, since this life form group was the focus of the harvesting operation. The few losses of palm trees and tree ferns occurred only as collateral damages of the harvesting operations. A relevant result was the dominance of *Euterpe edulis* among the recruited trees (DBH > 5.0 cm) two years after harvesting (Fig. 2), the only life form group whose density increased. Palm heart from *Euterpe edulis* is one of the most important non-timber forestry products in the Atlantic Forest (Fantini and Guries 2007), and its increased growth after a tree harvesting points out another economic benefit of managing secondary forests, especially considering its potential for producing revenue between harvesting cycles of trees. Although diverse studies suggested the potential economic management of the *Euterpe edulis* (Fantini and Guries 2007; Paludo et al. 2012; Pizo and Simão 2001; Reis et al. 2000), additional research is still needed to clarify the overall impact timber harvesting on its population and to guide silvicultural systems fit to multipurpose forest management.. The inventory of regenerants (trees below 5.0 cm DBH and above 1.3 m height) two years after harvesting reveals that new individuals are monthly from tree species in all stands and harvesting methods. While single-tree harvesting favored the growth of already existing palm tree species, it benefitted the regeneration of woody tree species.

All stands were dominated by trees bigger than 5.0 cm DBH belonging to secondary species before harvesting. Villela et al. (2006) also reported the predominance of secondary species in Atlantic Forest stands. However, timber harvesting is expected to change forest structure, in particular the opening canopy gaps of varied sizes (Darrigo

Table 6 Recovery and mortality rates two years after harvesting considering multiple damages on the same tree

Harvesting method	Damage category	Damaged trees immediately after harvesting	Dead trees (2 years)		Completely recovered (2 years)(N)		Partially recovered (2 years)(N)		Same damage (2 years)	
		(N)	(N)	(%)	(N)	(%)	(N)	(%)	(N)	(%)
CM	Only crown damages	70	14	20%	9	13%	16	23%	31	44%
	Only bole damages	69	7	10%	26	38%	6	9%	30	43%
	Only leaning Trees	1	1	100%	0	0%	0	0%	0	0%
	Combined crown and bole damages	62	12	19%	7	11%	19	31%	24	39%
	Combined crown and leaning damages	2	1	50%	0	0%	1	50%	0	0%
	Combined bole and leaning damages	7	2	29%	0	0%	1	14%	4	57%
	Combined crown, bole, and leaning damages	8	4	50%	0	0%	1	*13%*	3	38%
AM	Only crown damages	67	2	3%	13	19%	15	22%	37	55%
	Only bole damages	73	14	19%	22	30%	2	3%	35	48%
	Only leaning Trees	9	3	33%	3	33%	0	0%	3	33%
	Combined crown and bole damages	39	7	18%	4	10%	12	31%	16	41%
	Combined crown and leaning damages	13	3	23%	1	8%	4	31%	5	38%
	Combined bole and leaning damages	5	2	40%	1	20%	0	0%	2	40%
	Combined crown, bole, and leaning damages	4	3	75%	0	0%	0	0%	1	25%

The percentages indicate the proportion of remnant damaged trees two years after harvesting in relation to the number of damaged trees immediately after harvesting

Table 7 Recovery rates for crown damages considering recorded damage intensity immediately after harvesting (After) and two years after harvesting (2 years), under conventional (CM) and alternative (AM) harvesting methods

Harvesting-method	DamageIntensity	Immediately after harvesting	No damage (2 years)		Light (2 years)		Moderate (2 years)		Severe (2 years)		Dead (2 years)	
		(N)	(N)	(%)	(N)	(%)	(N)	(%)	(N)	(%)	(N)	(%)
CM	Light	50	15	30%	27	54%	0	0%	0	0%	8	16%
	Moderate	55	2	4%	15	27%	26	47%	0	0%	12	22%
	Severe	37	0	0%	5	14%	16	43%	5	14%	11	30%
AM	Light	51	13	25%	30	59%	0	0%	0	0%	4	8%
	Moderate	41	3	7%	11	27%	22	54%	0	0%	7	17%
	Severe	31	2	6%	4	13%	16	52%	7	23%	1	3%

N = number of damaged trees per classes of damage intensity of crown damages. The percentages indicate the proportion of remnant damaged trees two years after harvesting compared to the number of damaged trees immediately after harvesting

Table 8 Recovery rates for stem damages considering recorded damage intensity immediately after harvesting (After) and two years after harvesting (2 years), under conventional (CM) and alternative (AM) harvesting methods

Harvesting-method	Damage Intensity	Immediately after harvesting	No damage (2 years)		Light (2 years)		Moderate (2 years)		Severe (2 years)		Dead (2 years)	
		(N)	(N)	(%)	(N)	(%)	(N)	(%)	(N)	(%)	(N)	(%)
CM	Light	88	36	41%	39	44%	0	0%	0	0%	4	5%
	Moderate	50	6	12%	8	16%	26	52%	0	0%	3	6%
	Severe	8	4	50%	0	0%	1	13%	1	13%	1	13%
AM	Light	70	27	39%	35	50%	0	0%	0	0%	5	7%
	Moderate	35	3	9%	3	9%	14	40%	0	0%	10	29%
	Severe	16	5	31%	1	6%	3	19%	4	25%	3	19%

N = number of damaged trees per classes of damage intensity of stem damages. The percentages indicate the proportion of remnant damaged trees two years after harvesting compared to the number of damaged trees immediately after harvesting

Table 9 Recovery rates for leaning damages considering recorded damage intensity immediately after harvesting (After) and two years after harvesting (2 years), under conventional (CM) and alternative (AM) harvesting methods

Harvesting-method	Damage Intensity	Immediately after harvesting	No damage (2 years)		Light (2 years)		Moderate (2 years)		Severe (2 years)		Dead (2 years)	
		(N)	(N)	(%)	(N)	(%)	(N)	(%)	(N)	(%)	(N)	(%)
CM	Light	11	1	9%	5	45%	0	0%	0	0%	5	45%
	Moderate	5	0	0%	0	0%	3	60%	0	0%	2	40%
	Severe	2	0	0%	0	0%	1	0%	0	0%	1	0%
AM	Light	27	4	15%	15	56%	0	0%	0	0%	8	0%
	Moderate	4	1	25%	0	0%	0	0%	0	0%	3	0%
	Severe	0	0	0%	0	0%	0	0%	0	0%	0	0%

N = number of damaged trees per classes of damage intensity of leaning damages. The percentages indicate the proportion of remnant damaged trees two years after harvesting compared to the number of damaged trees immediately after harvesting

et al. 2016). Gap size, which is related to logging intensity, will promote the growth of undesired pioneer species of low commercial value or the growth of commercial (shade intolerant) species (Silva and Vibrans 2019). Increased solar radiation on the forest floor following tree harvesting also induces severe changes on the microclimate above and below ground (Swaine and Whitmore 1988). Pioneer species are more susceptible to impacts of forest timber harvesting than species of other ecological groups up to five years (Dionisio et al. 2017). Duah-Gyamfi et al. (2014) in a

Table 10 Binary logistic regression models for the mortality and recovery rates two years after harvesting

Model	Dependent Variable	Nagelkerke $R.^2$	Hosmer and Lemeshow Test		Constant / Coefficient		Sig
			Chi-square	sig			
Mortality rate	Y_{Dead}	0.105	5.141	0.643	−3.18		<0.001
					0.49	X_{Stand}	0.005
					0.72	X_{Stem}	0.020
					0.93	$X_{Leaning}$	<0.001
Recovery Rates	Y_{Rec}	0.231	11.491	0.119	0.411		0.195
					−1.318	X_{Crown}	< .001
					−0.773	X_{Stem}	0.001
					−1.070	$X_{Leaning}$	<0.019

Y_{Dead} = mortality rates two years after harvesting; Y_{Rec} = rates of completely recovered trees two years after harvesting; X_{Stand} = harvested stand (where stand $A = 1$, stand $B = 2$ and stand $C = 3$); X_{Stem} = stem damages immediately after harvesting; $X_{Leaning}$ = Leaning damages immediately after harvesting; and X_{Crown} = Crown damages immediately after harvesting

tropical forest on Ghana observed most of the tallest trees seven years after timber harvesting were pioneer timber species while non-pioneer species were numerically dominant. Silva and Vibrans (2019) suggested a conservative maximum logging intensity of 30% of the forest basal area to moderate changes of canopy cover in secondary Atlantic forests of the ERF. In this study, secondary species represented the majority of recruited individuals (above 5.0 cm DBH) two years after harvesting. However, among the regenerants (DBH < 5.0 cm; height > 1.3 m) pioneer species were predominant in all plots, another indication of the increase in growth rates of secondary species already established in the stands before harvesting. With respect to new regenerants, the canopy openings promoted a major increase of pioneer species. Subsequent inventories of the studied forest are needed to confirm continuous growth of secondary species or their replacement by upcoming pioneer species. Further research should also focus on the size and distribution of canopy openings and their impact on the regrowth of pioneer and secondary species, aiming to guide stand regeneration.

AM harvesting aided by auxiliary tools is supposed to cause a less damage on regenerants compared to CM harvesting. In this study, AM along with the use of skidding cone and snatch block for stem extraction helped to reduce the damage on regenerants by 5%. Other researchers also observed a reduction in damages with the use of skidding cones (Britto et al. 2019; Picchio et al. 2019). Moreover, the number of regenerants was even higher two years after harvesting than that recorded before harvesting. Besides the significant reduction in damages attributed to the use of a skidding cone and a snatch block, regrowth of pioneer species suggests that the forest dynamics may reduce such positive effects as fast-growing pioneer species outcompete the established secondary species.

It is remarkable that 41% of all remnant living trees were damaged during timber harvesting operations. CM stands showed a slightly higher number of damaged trees (219) compared to AM stands (210), although the difference was not statistically significant. Both harvesting methods led to a high number of crown damages. However, while most of the CM-induced crown damages were of moderate degree, AM caused mostly light crown damages. In addition, the number of severe damages was slightly higher for CM (52 trees) compared to AM (40 trees). Although a significant recovery of all crown damage intensities was observed two years after harvesting, a higher mortality rate of damaged trees was observed in CM stands, mainly of trees with severe damages, compared to AM stands. A recovery of stem damages two years after harvesting was also observed, while leaning trees showed high rates of mortality during the same period. Leaning trees, however, represented only 5% of all remnant trees after harvesting.

The binary logistic regression showed that the mortality rates over time might be higher in stands composed by a high density of smaller trees (stand C) compared to stands characterized by commercial trees of comparatively larger dimensions (DBH and height) (stand A). Higher intensities of stem and leaning damages may also cause higher mortality rates. Crown, stem and leaning damages also presented a negative effect on the recovery rates.

Conclusions

We did not find significant differences between the impacts of the two harvesting methods on damaged trees two years after harvesting. However, our results suggest potential effects on forest ecology and diversity. Two years after harvesting, the majority of trees (DBH above 5 cm) were those already established in the forest before harvesting (palm trees and secondary species). Stands with greater density of smaller trees and higher harvesting intensity showed increased mortality rates over time. Regenerants (DBH < 5 cm; tree height > 1.3 m) were mostly pioneer tree species. Single tree harvesting promoted a higher number of regenerants two years after harvesting compared to the number of pre-harvesting regenerants. Furthermore, the AM reduced damaged to regeneration by 5 %.

In CM, most of the damaged trees were in the moderate to severe category, while in AM, only light to moderate damages were recorded. The majority of damaged trees with moderate and light damages recovered by at least one damage assessment class. However, most of the trees with severe damages due to harvesting died within the next two years. Crown damages were not linked to mortality rates, yet high intensity of crown damages reduced the recovery rates over the 2-year study period. Higher mortality rate and lower recovery rate were observed for stands with a high intensity of stem and leaning damages.

Both harvesting methods showed consistent results in reducing damage during harvesting, helping to preserve a great number of species. Nevertheless, AM method proved that even relatively small improvements may reduce negative harvest impacts. The Atlantic Forest, by its turn, demonstrated great resilience and recovery capacity, even after a short period of time (two years).

The results of this study indicate that if conducted in a responsible way, timber utilization can generate income to landowners without necessarily reducing the ecological functions provided by the forest ecosystem. However, although promising, these results are yet preliminary and restricted to the scale of this case study. Further studies, covering larger and more diverse research areas, with a longer successive inventory scheme, are required to identify potential changes of forest growth dynamics because of harvesting intensity and methods.

Acknowledgements The authors very much appreciated the support from Clemente Bizewisky and Cristiano Bizewisky; Marlos Schmidt from TAJFUN Brazil; Tropical Forest Institute (IFT); Institute for the Environment of Santa Catarina (IMA), Sarunas Jomatas; Heitor Felippe Uller; Aline Klitzke; Gabriel Bollmann, Erica Pereira, Gisele Taruhn de Matos, Gefferson Elias Piazza and Brendan Nicholas Marais.

Author contributions PCB, DJ, SH, RCGR, ACV and ACF were involved in conceptualization; PCB was involved in data curation; PCB and DJ were involved in formal analysis; PCB, DJ, ACV and ACF were involved in funding acquisition; PCB and SH were involved in investigation; PCB, DJ and ACF were involved in methodology; PCB, DJ and ACF were involved in project administration; DJ and ACF were involved in supervision; PCB and DJ were involved in writing—original draft; and PCB, DJ, SH, RCGR, ACV and ACF were involved in writing—review and editing.

Funding Open Access funding enabled and organized by Projekt DEAL. The authors would like to express their sincere thanks for the financial support from Barbara und Elisabeth Grammel Studienstiftung and from the foundation of the Research and Innovation of the State of Santa Catarina (FAPESC) and, in particular, for the financial support by Eva Mayr-Stihl Stiftung. Further financial support was received by Georg Ludwig-Hartig Stiftung and Wissenschaftliche Gesellschaft Freiburg. A. C. Fantini and A. C. Vibrans received research scholarships from Brazilian National Council for Scientific and Technological Development (CNPq).

Availability of data and material The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest There are no conflicts of interests among the authors of the submitted manuscript.

References

Alarcon GG, Caporal DS, Beltrame ADV, Karam KF (2011) Transformação da paisagem e o uso dos recursos florestais na agricultura familiar: um estudo de caso em área de Mata Atlântica. Ciência Florestal 21(2) (in Portuguese). Doi: https://doi.org/10.5902/198050983242

Alvares CA, Stape JL, Sentelhas PC, de Moraes Gonçalves JL, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorol Z 22:711–728. https://doi.org/10.1127/0941-2948/2013/0507

Bennett LT, Adams MA (2004) Assessment of ecological effects due to forest harvesting: approaches and statistical issues. J Appl Ecol 41:585–598

Britto PC, Jaeger D, Hoffmann S, Robert RCG, Fantini AC, Vibrans AC (2017) Productivity assessment of timber harvesting techniques for supporting sustainable forest management of secondary Atlantic Forests in southern Brazil. Ann For Res 60:203–215. Doi: https://doi.org/10.15287/afr.2017.898

Britto PC, Jaeger D, Hoffmann S, Robert RCG, Vibrans AC, Fantini AC (2019) Impact assessment of timber harvesting operations for enhancing sustainable management in a secondary Atlantic Forest. Sustainability 11:6272. https://doi.org/10.3390/su11226272

Bulfe NML, Galvão F, Filho AF, Donagh PM (2009) Efeitos da exploração convencional e de impacto reduzido em uma floresta estacional semidecidual na província de Misiones, nordeste da Argentina. Floresta 39(2) (in Portuguese). Doi: https://doi.org/10.5380/rf.v39i2.14563

Canetti A, Braz EM, Mattos PP, Basso RO, Figueiredo Filho A (2021) A new approach to maximize the wood production in the sustainable management of Amazon forest. Ann for Sci 78:67. https://doi.org/10.1007/s13595-021-01079-8

Darrigo MR, Venticinque EM, Santos FAM (2016) Effects of reduced impact logging on the forest regeneration in the central Amazonia. For Ecol Manage Special Sect for Manage Clim Change 360:52–59. https://doi.org/10.1016/j.foreco.2015.10.012

Dionisio LFS, Schwartz G, Lopes JC, Oliveira FA (2018) Growth, mortality, and recruitment of tree species in an Amazonian rainforest over 13 years of reduced impact logging. For Ecol Manage 430:150–156. https://doi.org/10.1016/j.foreco.2018.08.024

Dionisio LFS, Schwartz G, Mazzei L, Lopes JC, Santos GGA, Oliveira FA (2017) Mortality of stocking commercial trees after reduced impact logging in eastern Amazonia. For Ecol Manage 401:1–7. https://doi.org/10.1016/j.foreco.2017.06.060

Duah-Gyamfi A, Swaine EK, Adam KA, Pinard MA, Swaine MD (2014) Can harvesting for timber in tropical forest enhance timber tree regeneration? For Ecol Manage 314:26–37. https://doi.org/10.1016/j.foreco.2013.11.025

Fantini AC, Guries RP (2007) Forest structure and productivity of palmiteiro (Euterpe edulis Martius) in the Brazilian Mata Atlântica. For Ecol Manag 242:185–194. https://doi.org/10.1016/j.foreco.2007.01.005

Fantini AC, Schuch C, Siminski A, Siddique I (2019) Small-scale management of secondary forests in the Brazilian Atlantic Forest. Floresta e Ambiente 26:69017. https://doi.org/10.1590/2179-8087.069017

Fantini AC, Siminski A (2017) Manejo de florestas secundárias da Mata Atlântica para produção de madeira: possível e desejável. Revista Brasileira de Pós-graduação 13 (in Portuguese). Doi: https://doi.org/10.21713/2358-2332.2016.v13.1013

Gourlet-Fleury S, Beina D, Fayolle A, Ouédraogo DY, Mortier F, Bénédet F, Closset-Kopp D, Decocq G (2013) Silvicultural disturbance has little impact on tree species diversity in a Central African moist forest. For Ecol Manage 304:322–332. https://doi.org/10.1016/j.foreco.2013.05.021

Jacobsen TR (2003) Populating the environment: human growth, density and migration in the Atlantic Forest. In: Galindo-Leal C, Câmara IDG (ed) The Atlantic Forest of South America: biodiversity, threats, and outlook. pp 426–435.

Joly CA, Metzger JP, Tabarelli M (2014) Experiences from the Brazilian Atlantic Forest: ecological findings and conservation initiatives. New Phytol 204:459–473

Karsten RJ, Jovanovic M, Meilby H, Perales E, Reynel C (2013) Regeneration in canopy gaps of tierra-firme forest in the Peruvian Amazon: comparing reduced impact logging and natural, unmanaged forests. For Ecol Manage 310:663–671. https://doi.org/10.1016/j.foreco.2013.09.006

Kengen S (2019) Forestry in Brazil: a brief history. Brasilia D.F. p 101.

Lingner DV, Schorn LA, Sevegnani L, Gasper AL, Meyer L, Vibrans AC (2015) Floresta ombrófila densa de Santa Catarina, Brasil: agrupamento e ordenação baseados em amostragem sistemática. Ciência Florestal 25 (in Portuguese). Doi: https://doi.org/10.5902/1980509820595

Magnusson WE, Lima OP, Quintiliano RF, Higuchi N, Ferreira Ramos J (1999) Logging activity and tree regeneration in an Amazonian forest. For Ecol Manag 113:67–74. https://doi.org/10.1016/S0378-1127(98)00418-6

Metzger JP (2009) Conservation issues in the Brazilian Atlantic forest. Biol Conserv 142(6):1138–1140. https://doi.org/10.1016/j.biocon.2008.10.012

Nagaike T, Hayashi A (2004) Effects of extending rotation period on plant species diversity in *Larix kaempferi* plantations in central Japan. Ann for Sci 61:197–202

Oliveira LZ, Gasper AL, Lingner DV, Sevegnani L, Vibrans AC (2019) Secondary subtropical Atlantic forests shelter a surprising number of rare tree species: outcomes of an assessment using spatially unbiased data. Biodivers Conserv 28:751–768. https://doi.org/10.1007/s10531-018-01690-8

Oliveira LZ, Klitzke AR, Fantini AC, Uller HF, Correia J, Vibrans AC (2018) Robust volumetric models for supporting the management of secondary forest stands in the Southern Brazilian Atlantic Forest. An Acad Bras Ciênc 90:3729–3744. https://doi.org/10.1590/0001-3765201820180111

Paludo GF, Silva JZ, Reis MS (2012) Estimativas de produção de frutos de palmiteiro (*Euterpe edulis Mart.*) a partir da densidade de indivíduos. Biodiversidade Brasileira 2:92–102 ((**in Portuguese**))

Peña-Claros M, Fredericksen TS, Alarcón A, Blate GM, Choque U, Leaño C, Licona JC, Mostacedo B, Pariona W, Villegas Z, Putz FE (2008) Beyond reduced-impact logging: Silvicultural treatments to increase growth rates of tropical trees. For Ecol Manage Moving beyond Reduced Impact Logging towards More Holistic Manage Trop for 256:1458–1467. https://doi.org/10.1016/j.foreco.2007.11.013

Piazza GE, Zambiazi DC, Correia J, Fantini AC (2017) Regeneração natural de espécies madeireiras na floresta secundária da Mata Atlântica. Adv for Sci 4(2):99–105 ((**in Portuguese**))

Picchio R, Tavankar F, Bonyad A, Mederski PS, Venanzi R, Nikooy M (2019) Detailed analysis of residual stand damage due to winching on steep terrains. Small Scale for 18:255–277. https://doi.org/10.1007/s11842-019-09417-5

van der Pijl L (1969) Principles of dispersal in higher Plants. Springer-Verlag, Heidelberg. https://doi.org/10.1007/978-3-662-00799-0

Pinto LP, Brito MCW (2003) Dynamics of biodiversity loss in the Brazilian Atlantic Forest: an introduction. In: Galindo-Leal C, Camara IG (eds) The Atlantic Forest of South America: biodiversity status, trends, and outlook. Center for Applied Biodiversity Science and Island Press, Washington, pp 12–26

Pizo MA, Simão I (200) Seed deposition patterns and the survival of seeds and seedlings of the palm Euterpe edulis. Acta Oecologica 22:229–233. Doi: https://doi.org/10.1016/S1146-609X(01)01108-0

Putz FE, Sist P, Fredericksen T, Dykstra D (2008) Reduced-impact logging: challenges and opportunities. For Ecol Manag 256:1427–1433. https://doi.org/10.1016/j.foreco.2008.03.036

Reis MS, Fantini AC, Nodari RO, Reis A, Guerra MP, Mantovani A (2000) Management and Conservation of natural populations in Atlantic Rain Forest: the case study of palm heart (*Euterpe edulis Martius*). Biotropica 32:894–902. https://doi.org/10.1111/j.1744-7429.2000.tb00627.x

Reitz R (1965) Collection plan. In: Reitz R (ed) Illustrated Flora of Santa Catarina. Plano de coleção. Flora Ilustrada de Santa Catarina. Herbário Barbosa Rodrigues, Itajaí, SC, Brazil.

Ribeiro MC, Metzger JP, Martensen AC, Ponzoni FJ, Hirota MM (2009) The Brazilian Atlantic Forest: How much is left, and how is the remaining forest distributed? Implications for conservation. Biol Conserv 142:1141–1153. https://doi.org/10.1016/j.biocon.2009.02.021

Ruy CC, Weiser NH, Piazza GE, Robert RCG (2014) Danos decorrentes do uso da floresta baseado em conhecimentos tradicionais: Um estudo de caso em uma floresta secundária de Santa Catarina. Enciclopédia Biosfera 10:2869–2878 (**in Portuguese**)

Santos LD, Schlindwein SL, Fantini AC, Belderrain MCN, Montibeller G, Franco LA (2019) Structuring contrasting forest stakeholders' views with the strategic options development and analysis (SODA) approach. Int for Rev 21:501–515. https://doi.org/10.1505/146554819827906834

Silva DA, Piazza G, Fantini AC, Vibrans AC (2018) Forest management in a secondary Atlantic rainforest: assessing the harvest damage. Adv for Sci 4:187–193

Silva DA, Vibrans AC (2019) Canopy architecture after selective logging in a secondary Atlantic Rainforest in Brazil. Floresta e Ambiente 26:37418. https://doi.org/10.1590/2179-8087.037418

Silva JMC, Casteleti CHM (2003) Status of the biodiversity of the Atlantic Forest of Brazil. In: Galindo-Leal C, Camara IG (eds)

The Atlantic Forest of South America: biodiversity status, trends, and outlook. Center for Applied Biodiversity Science and Island Press, Washington, D.C, pp 43–59

Silva WG, Metzger JP, Simões S, Simonetti C (2007) Relief influence on the spatial distribution of the Atlantic Forest cover on the Ibiúna Plateau. SP Brazil J Biol 67(3):403–411. https://doi.org/10.1590/S1519-69842007000300004

Swaine MD, Whitmore TC (1988) On the definition of ecological species groups in tropical rain forests. Vegetation 75:81–86. https://doi.org/10.1007/BF00044629

Tavankar F, Bonyad AE (2015) Effects of timber harvest on structural diversity and species composition in hardwood forests. Biodiversitas 16:1–9. Doi: https://doi.org/10.13057/biodiv/d160101

Trevisan ACD, Schmitt-Filho AL, Farley J, Fantini AC, Longo C (2016) Farmer perceptions, policy and reforestation in Santa Catarina, Brazil. Ecol Econ 130:53–63. https://doi.org/10.1016/j.ecolecon.2016.06.024

Uuttera J, Maltamo M, Hotanen JP (1997) The structure of forest stands in virgin and managed peat lands: a comparison between Finnish and Russian Karelia. For Ecol Manage 96:125–138

Uller HF, Oliveira LZ, Klitzke AR, Freitas JV, Vibrans AC (2021) Biomass models for three species with different growth forms and geographic distribution in the Brazilian Atlantic Forest. Can J for Res 51:1–13

Uller HF, Oliveira LZ, Vibrans AC, Klitzke AR, Eleotério JR (2019) Aboveground biomass quantification and tree-level prediction models for the Brazilian subtropical Atlantic Forest. Southern Forests; 81:261–271

Vibrans AC, Sevegnani L, Gasper AL, Lingner DV (2012) Inventário florístico florestal de Santa Catarina. Vol. 1: Diversidade e conservação dos remanescentes florestais. Universidade Regional de Blumenau, Blumenau.

Vibrans AC, McRoberts RE, Moser P, Nicoletti AL (2013) Using satellite image-based maps and ground inventory data to estimate the area of the remaining Atlantic forest in the Brazilian state of Santa Catarina. Remote Sens. Environ. 130: 87–95. https://doi.org/10.1016/j.rse.2012.10.023

Villela DM, Nascimento MT, Aragao LEOC, da Gama DM (2006) Effect of selective logging on forest structure and nutrient cycling in a seasonally dry Brazilian Atlantic forest. J Biogeogr 33(3):506–516. https://doi.org/10.1111/j.1365-2699.2005.01453.x

Zambiazi DC, Fantini AC, Piotto D, Siminski A, Vibrans AC, Oller DC, Piazza GE, Peña-Claros M (2021) Timber stock recovery in a chronosequence of secondary forests in Southern Brazil: Adding value to restored landscapes. For Ecol Manage 495:119352. https://doi.org/10.1016/j.foreco.2021.119352

Authors and Affiliations

Pedro Caldas Britto[1] · Dirk Jaeger[1] · Stephan Hoffmann[2] · Renato Cesar Gonçalves Robert[3] · Alexander Christian Vibrans[4] · Alfredo Celso Fantini[5]

[1] Department of Forest Work Science and Engineering, University of Göttingen, Buesgenweg 4, 37077 Göttingen, Germany

[2] Division of Forest and Forest Resources, Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway

[3] Forestry & Wood Science Center, Federal University of Paraná (UFPR), Av. Prefeito Lothário Meissner 632, Curitiba 80210-170, Brazil

[4] Department of Forest Engineering, University of Blumenau (FURB), R. São Paulo 3250, Blumenau 89030-000, Brazil

[5] Laboratory of Ecology and Management of Forest Ecosystems, Federal University of Santa Catarina (UFSC), Rodovia Admar Gonzaga 1346, Florianopolis 88034-000, Brazil