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Impact Assessment of Timber Harvesting Operations for Enhancing Sustainable Management in a Secondary Atlantic Forest

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Abstract: Conservation and management of forest ecosystems are currently largely conflicting goals in the Brazilian Atlantic Forest biome. At present, all parts of the Atlantic Forest are protected and commercial logging is highly restricted. However, sustainable forest management systems can offer significant income opportunities for landholders, and thereby actively support the process of ecosystem rehabilitation and protection of the Atlantic Forest. This research is intended to contribute to enhancing the development of environmentally sound forest management alternatives in the Atlantic Forest biome. Through a case study, the harvesting impact of a conventional harvesting method (CM) was evaluated and compared with an alternative and improved harvesting method (AM), performed by a well-trained professional chainsaw operator experienced in reduced impact logging techniques, and included the use of a snatch block and a skidding cone. Following a full pre-harvest inventory, 110 different tree species were identified. The harvesting impact on the residual stand was classified and evaluated through a successive post-harvest inventory. Damage maps were developed based on interpolation of tree damage intensities with the triangular irregular networks (TIN) methodology. Our results showed noticeable high rates of tree hang-ups, observed for both harvesting methods. Furthermore, the harvesting damaged trees mainly in the lower diameter at breast height (DBH) classes. In comparison to winching, the felling process caused most of the damage to remnant trees for both methods, at 87% (CM) and 88% (AM). The number of damaged trees (above 11.9 cm DBH) per harvested tree, for CM, ranged from 0.8 trees to 2.5 trees and, for AM, ranged from 0.6 trees to 2.2 trees. Improvements of the AM method (operator skills, skidding cone and snatch block) over CM allowed for a reduction of the damaged basal area, a reduction of the "high damaged area" per plot, and a reduction of the winching disturbed ground area. Nonetheless, a suitable harvesting system should consider further improvements in the felling technique, and additionally integrate the local knowledge of CM regarding forest and tree species with the technical improvements of AM.

Keywords: tractor winch; chainsaw; skidding cone; snatch block; ArcGIS

1. Introduction

Brazil's Atlantic Forest originally covered approximately 150 million hectares, being one of the largest rainforests in America [1]. Home to two-thirds of Brazil's population [2] and exceptionally rich in biodiversity, it is the most threatened biome in Brazil [3]. The forest land area decreased to only 12% of its original extent [4], mainly as a result of intensive exploitation and conversion to other land-uses such as agriculture, plantation forests, and expanding urbanization [5]. Furthermore, most of the remaining Atlantic Forest is fragmented into small (less than 50 ha) and isolated forest patches, mainly covered with second growth forests [4,5] and owned by private landowners [1]. In Santa Catarina State, southern Brazil, secondary forests represent 95% of the remaining forest cover [6]. Virtually all of these forests regenerated naturally after the abandonment of land previously used for crop or pasture cultivation [5,7].

Conservation and management of the remaining forest ecosystem are currently largely conflicting goals in the biome [8]. Irrespective of size of forest patches, commercial logging is banned by forest regulations issued in 1993 and 2006, aiming at protecting the remnant forests from deforestation and degradation [5]. The effectiveness of such policy is, however, questionable. Various researchers argued that sustainable management of secondary forests providing income opportunities would be more effective in increasing the willingness of land owners to conserve and possibly even expand the forest, favoring local development through income generation [3,5,8–12].

Multiple studies have investigated the potential of secondary forest utilization in tropical regions [3,7,8]. However, although the Atlantic secondary forests may reach high productivity due to several fast growing species [8,11], only few studies have evaluated the utilization potential of these forests for timber production. Fantini and Siminski [5] estimated the amount of commercially mature trees at up to 300 trees per ha (diameter at breast height above 15 cm), corresponding to a harvestable timber volume of 30 million m^3, within the approximately 6000 km^2 of secondary forests of the evergreen rainforests (ERF) of the Santa Catarina State alone. These authors also mention that secondary forests of the region can reach a volume of 50 m^3 ha^{-1} for mature trees of fast growing merchantable species by 30 to 35 years of age.

Alarcon et al. [9] highlighted the importance of research to support alternative management strategies, including potential utilization of native trees from the Atlantic Forest biome through regulated timber harvesting. Despite its relevance, only a few studies on timber harvesting systems and related impacts on forest stands have been done in the Atlantic Forest biome [10,12–14]. According to Spinelli et al. [15], physical damage to the residual stand is driven by several factors such as the harvesting system, site and stand characteristics, harvesting intensity, skills of operators, and extraction systems, including the layout of skid trails. The harvesting damages may range from timber quality loss and reduced forest growth in subsequent growing seasons to, in the worst cases, the mortality of remnant trees. Although the damages resulting from harvesting operations are inevitable [16], they can be significantly reduced with a harvesting system that is appropriate and adequate to local forest conditions. Hence, for the Atlantic Forest biome, Silva et al. [12] reinforced the importance of evaluating the damage observed in local harvesting systems as well as in a viable alternative of reduced impact logging systems.

An appropriate timber harvesting method is fundamental for economically viable and environmentally sound forest management plans [10]. Our goal is, therefore, to contribute to fill the current knowledge gap on harvesting method and forest utilization in secondary forests by evaluating the damage caused during timber harvesting and log extraction. Hence, in this study, we evaluated the impacts of two different harvesting methods in three secondary forest stands with different structures and terrain slopes. Through a case study approach, we studied: (a) the influence of terrain and stand structure on the damage caused by harvesting on remnant trees; (b) the effectiveness of improving the harvesting operations to a proposed harvesting system (here called the Alternative Method—AM) with the regionally widespread traditional harvesting system (the Conventional Method—CM). Furthermore, we also investigated both harvesting methods for the

potential significance of felling directions and winching lines on the number and location of damaged remnant trees and stand areas with high concentration of damaged trees. Finally, we suggested some improvements for the sustainable management of secondary forests in the Atlantic Forest region.

2. Materials and Methods

2.1. Research Area

The research was carried out in evergreen rainforests (ERF), which are one of the most common forest formations in the Atlantic Forest biome in southern Brazil [17]. The total size of the case study area was 42 ha. The forest cover consisted of a 35 year old second growth forest, regenerated after the abandonment of plots cultivated under swidden agricultural farming [10,12]. The Institute for the Environment of Santa Catarina (IMA) is one of the partners in this study and provided the exceptional permit for timber harvesting as part of long-term research. Therefore, our study site is a unique research area in the Atlantic Forest biome, serving as a pilot site to test and evaluate various alternative forest management regimes for sustainable forest management, including timber utilization. The site is located in the municipality of Guaramirim, in Santa Catarina State (26°32′10″ S and 49°02′38″ W, approximately). According to the Köppen classification, the climate in the region is subtropical humid with a hot summer and no dry season [18]. The local mean annual temperature is 20.9 °C and the mean annual precipitation is 1613 mm.

Three stands (A, B, and C) were selected within the study area. In order to compare the distinct harvesting methods, two 0.16 ha square plots were set in each stand, adding up to a total sampling area for the six plots of 0.96 ha. The plots were positioned along the forest roads and projected 60 m into the stand. In every plot, a pre-harvest inventory of all trees with diameter at breast height (DBH) above 7 cm over bark (o.b.), was conducted, recording tree species, DBH, tree height, and location (Cartesian X and Y coordinates). For the exact positioning of the trees, each plot was further subdivided into 16 subplots (100 m^2 each). In all the 96 subplots, the corners were demarcated with a PVC pipe. Measured trees were permanently marked with an aluminum tag, allowing for tree identification during the intended multi-year post-harvesting monitoring of the plots.

In all three stands, a similar harvesting intensity of 40% basal area reduction was targeted, as recommended by Silva et al. [12], based on studies at the same site analyzing the optimal harvesting intensity for the forest with respect to diverse regeneration (of shade intolerant and shade tolerant species). The harvesting operation included felling of commercial trees and noncommercial trees in the latter case for stand improvement. Commercial felling focused on mature trees of species of economic value to generate maximum revenue for the landowner, while improvement felling included harvesting of small trees with a low quality or economic value [10]. While all commercial felling included extraction of logs, most of the stems resulting from improvement felling remained in the stands except for those at close distance to a forest road, which were used as firewood.

2.2. Harvesting Methods

In this study, we compared a "Conventional Method" (CM) and an "Alternative Method" (AM) of harvesting. In both methods, trees were felled, delimbed, and bucked inside the stand using a chainsaw, while timber extraction was carried out using a winch fitted tractor. The tractor was always positioned outside of the stand, on the forest road and did not enter the forest stand. A coworker assisted the tractor operator in both methods, pulling out the cable from the winch to the log location inside the stand. The term "winching" in this paper refers to the process of extracting stems from the felling site to an adjacent forest road. The CM harvesting method was widely used to harvest the regional forests, whose operators are mostly people with extensive practical experience in tree felling but with no formal training.

In our case, CM tree felling was conducted by the forest owner, operating 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 33T) (Figure 1a). In contrast, AM was conducted by a contracted professional chainsaw operator, experienced in reduced impact logging techniques in the Amazon region. He executed the tree felling with a Stihl® chainsaw (model 661). The consecutive log extraction was conducted with a state of the art TAJFUN® winch (TAJFUN d.o.o., Planina/Slovenja) (model EGV 85 AHK), fitted to a 4 × 4 tractor (Figure 1b) and supplemented with a Portable Winch® skidding cone and a TAJFUN® snatch block (Figure 1c) [10].

| (**a**) | (**b**) | (**c**) |

Figure 1. Harvesting equipment used: (**a**) Standard 2 × 2 farm tractor with a TMO Caçador® winch used in the conventional method (CM); (**b**) TAJFUN® winch fitted on a 4 × 4-farm tractor used in the alternative method (AM); (**c**) Skidding cone and snatch block supplementing the AM extraction.

2.3. Analytical Methods

We compared the three stands' structural characteristics (non-parametric Whitney U Test, p < 0.05) stand density (number of trees per area), tree DBH, tree height, basal area (of trees ≥ 7 cm o. b.), and stocking volume. We also compared harvesting methods and stands with regards to harvested intensities, harvested basal area, and harvested volume. We performed two analyses; the first considering all the tree species within the stand, and the second considering only the commercial tree species. Additionally, tree hang-ups were recorded and further assessed according to stand characteristics and harvesting methods.

The damages to remnant trees caused by the harvesting were determined by visual inspection of all standing trees after completion of the harvesting operation and recorded as undamaged, damaged, or dead. Categorization and rating of damaged trees according to damage severity classes (minor, moderate, and severe) followed the methodology of Silva et al. [12] (Table 1).

Table 1. Classification criteria for harvesting damage to residual trees in a secondary Atlantic Forest according to Silva et al. [12].

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*

Causes of damage on standing remnant trees were further classified either as a) felling or b) winching. The damages caused by felling were usually evidenced by damages that were caused by the felling of neighboring trees and characterized by damages to the crown and vertical scratches at the bole at any height (Figure 2a). Typical damages caused by winching were characterized by horizontal scratches at the bole and observed up to one meter from the ground surface (Figure 2b).

(**a**)   (**b**)

Figure 2. Examples of damaging of the bole caused by the felling of neighboring trees (**a**) and by winching, during log extraction (**b**).

Statistical analyses (p < 0.05) were further applied to identify potential differences of the two harvesting methods and of stand and terrain conditions with respect to damage of remnant trees.

Using pre-harvest inventory data, every tagged tree was georeferenced with the transformation of its Cartesian coordinates (X, Y) into UTM coordinates (WGS 1984, Zone 22 South) to determine its position within the plot. Furthermore, the geoprocessing methodology "triangulated irregular network" (TIN) [19] within ArcGIS software version 10.5.1 (ESRI Inc., Redlands/USA) was used for generating damage maps based on damage intensity of remnant trees for visual assessments of damage locations.

The damage intensity on remnant trees was assigned a rating value ranging from zero (0) to nine (9) resulting from the sum of rating values of the damage severity classes (minor, moderate, and severe) on the three evaluated tree's regions (crown, bole, and leaning) as described in Table 1. Moreover, undamaged trees were assigned the lowest damage rating value (0), while not found and dead trees were assigned the highest scores (9). For TIN generation, the damage intensity scores replaced the values of terrain height (z-axis) generated on the map. Therefore, the highest values of height represented the most damaged areas in every plot and, thereafter, the lowest values of height represented the lowest damaged area per plot. Furthermore, within TIN analysis, lines of equal damage intensity were generated around the most damaged areas and further transformed into polygons to outline the size of most damaged areas into every research plot. Felling direction and winching line bearings, obtained with a field compass during the harvesting operation, were georeferenced, analyzed in ArcGIS, plotted on the maps according to the measured azimuth and position of trees within the stand and analyzed with respect to potential damages caused by the recorded felling and winching directions.

Additionally, we assessed the predominant slope direction of the plots with respect to each tree's felling direction and determined the correspondence between the terrain slope directions and the tree felling directions. These maps allowed for analyzing the location of most of the damaged trees with their felling direction, length of winching line, and size of disturbed ground area due to the winching operation, and terrain slope.

3. Results

3.1. Forest Structure and Harvesting Intensity

Within the six research plots, 110 different tree species were identified, representing nearly 20% of the 577 different species occurring in the Atlantic evergreen rainforest (ERF), as described by Lingner et al. [20]. Among the identified species, 38 were considered as commercial species [11], with a marketable timber value and of relevance for income generation to landowners. Within the small size of the research area (42 ha), there is a significant difference among stands for most of the forest structure and site characteristics (tree density, mean DBH, basal area, and standing volume) (Table 2).

Table 2. Main stand characteristics among plots.

	Stand A		Stand B		Stand C	
	CM	AM	CM	AM	CM	AM
All trees						
Tree density (N ha^{-1})	1600.0 [aA]	1331.3 [aA]	1456.3 [aA]	1393.8 [aA]	1625.0 [aB]	1887.5 [aB]
Mean DBH (cm)	14.8 [aA]	15.1 [aA]	12.7 [aB]	14.4 [aB]	13.0 [aC]	11.8 [aC]
Mean tree height (m)	9.7 [aA]	9.6 [aA]	10.0 [aA]	10.3 [aA]	10.1 [aA]	9.9 [aA]
Basal area (m^2 ha^{-1})	39.5 [aA]	37.6 [aA]	24.7 [aB]	30.1 [aB]	28.2 [aB]	29.2 [aB]
Volume (m^3 ha^{-1})	313.0 [aA]	259.3 [aA]	187.0 [aB]	211.5 [aB]	191.5 [aB]	195.2 [aB]
Commercial species						
Tree density (N ha^{-1})	456.3 [aB]	443.8 [aB]	456.3 [aB]	512.5 [aB]	675.0 [aA]	656.3 [aA]
Mean DBH (cm)	20.0 [aA]	19.2 [aA]	18.1 [aA]	19.4 [aA]	15.3 [aB]	13.1 [aB]
Mean tree height (m)	13.5 [aA]	13.1 [aA]	15.0 [aA]	13.9 [aA]	12.4 [aA]	11.8 [aA]
Basal area (m^2 ha^{-1})	18.4 [aA]	18.8 [aA]	15.0 [aAB]	17.6 [aAB]	14.7 [aB]	10.8 [aB]
Volume (m^3 ha^{-1})	147.5 [aA]	142.7 [aA]	127.7 [aAB]	133.0 [aAB]	108.5 [aB]	76.5 [aB]
Terrain slope (%)	≈ 40–50		≈ 10–25		≈ 5–10	

Different lowercase letters in the same line indicate significant differences between harvesting methods. Different capital letters in the same line indicate significant differences among stands.

In general, stand A was characterized by a steep terrain (≈ 50% slope) and bigger commercial trees, while stand C was located in a more flat terrain (≈ 5–10% slope) with a high density of smaller trees. Stand B represented some intermediary conditions between A and C, with more flat terrain (≈ 10–25%) but also with some bigger commercial trees.

According to the management plan and the target set, a high harvesting intensity was applied in all three stands (Table 3), especially in stand C (350.0 trees ha^{-1} for CM and 400.0 trees ha^{-1} for AM).

Table 3. Harvesting data and harvesting intensities for the conventional (CM) and the alternative (AM) harvesting methods across stands.

	Stand A		Stand B		Stand C	
	CM	AM	CM	AM	CM	AM
All harvested trees						
Harvesting intensity (N ha^{-1})	175.0 [aA]	118.8 [aA]	100.0 [aA]	137.5 [aA]	350.0 [aB]	400.0 [aB]
Harvested basal area (m^2 ha^{-1})	13.0 [aA]	10.4 [aA]	6.1 [aA]	8.5 [aA]	11.9 [aA]	10.3 [aA]
Harvested volume (m^3 ha^{-1})	104.1 [aA]	72.6 [aA]	52.9 [aA]	57.0 [aA]	79.3 [aA]	69.1 [aA]
Mean DBH (cm)	25.9 [aA]	30.0 [aA]	26.7 [aA]	24.2 [aA]	16.2 [aB]	12.2 [aB]
Mean tree height (m)	14.7 [aA]	15.4 [aA]	17.4 [aA]	13.8 [aA]	10.9 [aB]	10.8 [aB]
Winched trees (N ha^{-1})	118.8 [aA]	100.0 [aA]	68.8 [aA]	93.8 [aA]	106.3 [aA]	81.3 [aA]
Commercial felling						
Harvesting intensity (N ha^{-1})	106.3 [aA]	93.8 [aA]	62.5 [aAB]	81.3 [aAB]	81.3 [aB]	6.3 [bB]
Harvested basal area (m^2 ha^{-1})	9.6 [aA]	9.5 [aA]	4.9 [aAB]	6.2 [aAB]	4.6 [aB]	0.3 [bB]
Harvested volume (m^3 ha^{-1})	81.5 [aA]	67.1 [aA]	44.4 [aAB]	43.3 [aAB]	32.6 [aB]	2.2 [bB]
Mean DBH (cm)	34.1 [aA]	34.7 [aA]	31.5 [aA]	30.8 [aA]	24.8 [aB]	23.6 [aB]
Mean tree height (m)	17.8 [aA]	17.5 [aA]	20.6 [aA]	16.1 [aA]	12.4 [aB]	16.0 [aB]
Winched trees (N ha^{-1})	100.0 [aA]	93.8 [aA]	62.5 [aAB]	81.3 [aAB]	81.3 [aB]	6.3 [aB]

Table 3. *Cont.*

	Stand A		Stand B		Stand C	
	CM	**AM**	**CM**	**AM**	**CM**	**AM**
Improvement felling						
Harvesting intensity (N ha^{-1})	68.8 [aA]	25.0 [aA]	37.5 [aA]	56.3 [aA]	268.8 [aB]	393.8 [aB]
Harvested basal area (m^2 ha^{-1})	3.4 [aA]	0.9 [aA]	1.2 [aA]	2.3 [aA]	7.3 [aB]	10.0 [aB]
Harvested volume (m^3 ha^{-1})	22.5 [aA]	5.5 [aA]	8.6 [aA]	13.7 [aA]	46.7 [aB]	66.9 [aB]
Mean DBH (cm)	19.3 [aA]	18.0 [aA]	18.9 [aA]	18.1 [aA]	14.4 [aB]	12.1 [aB]
Mean tree height (m)	12.2 [aA]	10.3 [aA]	12.1 [aA]	11.7 [aA]	10.7 [aA]	10.8 [aA]
Winched trees (N ha^{-1})	18.8 [aAB]	6.3 [aAB]	6.3 [aA]	12.5 [aA]	25.0 [aB]	75.0 [aB]

Different lowercase letters in the same line indicate significant differences between harvesting methods. Different capital letters in the same line indicate significant differences among stands.

The significantly higher number of harvested trees in stand C resulted primarily from the focus on improvement felling (77% for CM and 98% for AM of total harvested trees), as this stand had a higher tree density of smaller trees with a high proportion of non-commercial trees. In contrast, the lower number of harvested trees in stand A (175.0 trees ha^{-1} for CM and 118.8 trees ha^{-1} for AM) and B (100.0 trees ha^{-1} for CM and 137.5 trees ha^{-1} for AM) resulted primarily from the focus on commercial felling. The commercial volume harvested in stand A was 81.5 m^3 ha^{-1} for CM and 67.1 m^3 ha^{-1} for AM and for stand B, 44.4 m^3 ha^{-1} for CM and 43.3 m^3 ha^{-1} for AM, which represented, in average, 85% (stand A) and 80% (stand B) of the total harvested volume.

There was a high number of tree hang-ups during the felling process, for both harvesting methods in all three stands (Figure 3). In stand C, characterized by the improvement cut of a high number of small trees, the highest rate of tree hang-ups was observed (59% for both methods). Stand B with more favorable terrain conditions, bigger trees, and lower tree density, presented the smallest rates of tree hang-ups, with 38% for CM and 41% for AM.
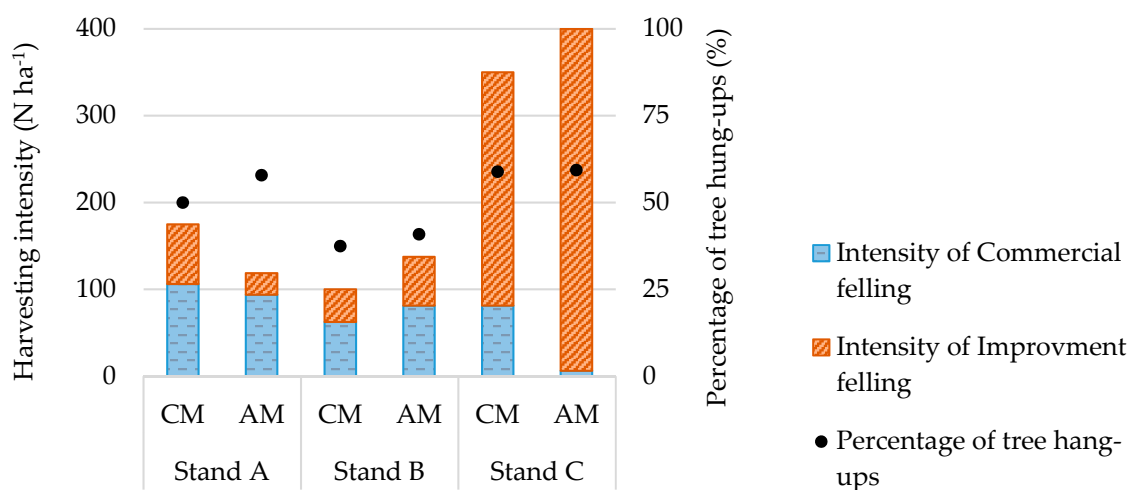
Figure 3. Harvesting intensity and tree hang-up rates for the conventional (CM) and alternative (AM) harvesting methods across the stands. Columns represent the harvesting intensity and black dots represent the percentage of tree hang-ups.

3.2. Harvesting Damage

With respect to terrain slope, no effect on damage of remnant trees was clear. Surprisingly, stand A, with the highest terrain slope (40–50%), showed the lowest degree of damaged basal area (29.2%) (including damaged and dead trees) and the lowest degree of damaged tree volume (28.0%) compared to stands B and C. In the moderately sloped stand B (10–25% slope), both the highest degree of damaged basal area and damaged volume (35.6% and 35.1%, respectively) was recorded. Stand C, with the

lowest terrain slope (5–10%), showed slightly lower degrees of damaged basal area and damaged volume (34.2% and 33.2%, respectively) (Table 4).

Table 4. Harvesting damage for the conventional (CM) and the alternative (AM) harvesting methods across stands considering all trees with DBH $\geq$ 7 cm o.b, including commercial tree species.

|	Stand A		Stand B		Stand C	
	CM	AM	CM	AM	CM	AM
All remnant trees (N ha^{-1})						
Total remnant trees	1425.0 [aA]	1225.0 [aA]	1356.3 [aA]	1256.3 [aA]	1268.8 [aA]	1487.5 [aA]
Undamaged trees	762.5 [aA]	618.8 [aA]	643.8 [aA]	668.8 [aA]	525.0 [aA]	618.8 [aA]
Damaged trees	387.5 [aA]	425.0 [aA]	450.0 [aA]	368.8 [aA]	462.5 [aA]	506.3 [aA]
Dead trees	275.0 [aA]	181.3 [aA]	262.5 [aA]	218.8 [aA]	281.3 [aA]	362.5 [aA]
Basal area (m^2 ha^{-1})						
Undamaged trees	14.3 [aA]	13.3 [aA]	8.8 [aA]	12.2 [aA]	7.0 [aA]	8.5 [aA]
Damaged trees	9.4 [aA]	7.4 [aA]	7.3 [aA]	7.4 [aA]	6.4 [aA]	7.0 [aA]
Dead trees	2.8 [aA]	1.7 [aA]	2.5 [aA]	2.2 [aA]	2.6 [aA]	3.5 [aA]
Volume (m^3 ha^{-1})						
Undamaged trees	102.5 [aA]	98.5 [aA]	61.8 [aA]	87.4 [aA]	49.8 [aA]	58.4 [aA]
Damaged trees	70.7 [aA]	51.5 [aA]	55.8 [aA]	53.6 [aA]	44.3 [aA]	46.3 [aA]
Dead trees	16.2 [aA]	9.5 [aA]	15.8 [aA]	13.3 [aA]	15.4 [aA]	21.7 [aA]
Commercial Trees(N ha^{-1})						
Remnant trees	356.3 [aA]	425.0 [aA]	412.5 [aA]	437.5 [aA]	631.3 [aB]	656.3 [aB]
Undamaged trees	181.3 [aA]	225.0 [aA]	162.5 [aA]	262.5 [aA]	262.5 [aA]	287.5 [aA]
Damaged trees	143.8 [aA]	137.5 [aA]	200.0 [aA]	137.5 [aA]	231.3 [aA]	243.8 [aA]
Dead trees	31.3 [aA]	62.5 [aA]	50.0 [aA]	37.5 [aA]	137.5 [aA]	125.0 [aA]
Commercial Basal area (m^2 ha^{-1})						
Undamaged trees	7.2 [aA]	8.6 [aA]	4.3 [aA]	7.1 [aA]	4.6 [aA]	5.5 [aA]
Damaged trees	4.9 [aA]	3.5 [aA]	5.4 [aA]	4.6 [aA]	3.9 [aA]	4.4 [aA]
Dead trees	0.2 [aA]	0.9 [aA]	0.8 [aA]	0.6 [aA]	1.4 [aA]	1.4 [aA]
Commercial Volume (m^3 ha^{-1})						
Undamaged trees	59.1 [aA]	70.3 [aA]	35.7 [aA]	56.1 [aA]	36.0 [aA]	39.3 [aA]
Damaged trees	39.1 [aA]	27.2 [aA]	45.3 [aA]	37.0 [aA]	28.7 [aA]	31.1 [aA]
Dead trees	1.5 [aA]	6.0 [aA]	6.3 [aA]	4.6 [aA]	9.5 [aA]	9.7 [aA]

Different lowercase letters in the same line indicate significant differences between harvesting methods. Different capital letters in the same line indicate significant differences among stands.

When comparing the impact of the two analyzed harvesting methods, stand A and stand B (mostly commercial felling and bigger trees), CM showed a higher degree of damaged basal area and damaged volume compared to AM. However, in stand C (mostly improvement felling and smaller trees) CM presented a lower degree of damaged basal area (32.4%) and damaged volume (31.6%) compared to AM (35.9% and 34.8% of damaged basal area and damaged volume, respectively). Moreover, it is important to mention that statistical analysis showed no significant difference between the two harvesting methods, nor among the three stands regarding the number of residual, undamaged, damaged and dead trees. There was also no statistically significant difference between the two methods with respect to the total number of damaged trees for all classes of damage, the total number of dead trees, and the corresponding basal area of damaged trees.

Furthermore, as expected, differences were found between causes of damage (felling or winching) to remnant trees inside the plots (Figure 4). Regardless of harvesting method or stand characteristics, felling was mostly responsible for damages.

For CM, felling damages varied from 30% (stand A) to 36% (stand B) and 40% (stand C) of damages on remnant trees. For AM, felling damages varied from 35% (stand A) to 36% (stand B) and 42% (stand C). Winching was responsible for 5% (CM) and 8% (AM) of the damages to remnant trees in stand A, 8% (CM) and 10% (AM) in stand B, and 14% (CM) and 6% (AM) in stand C.
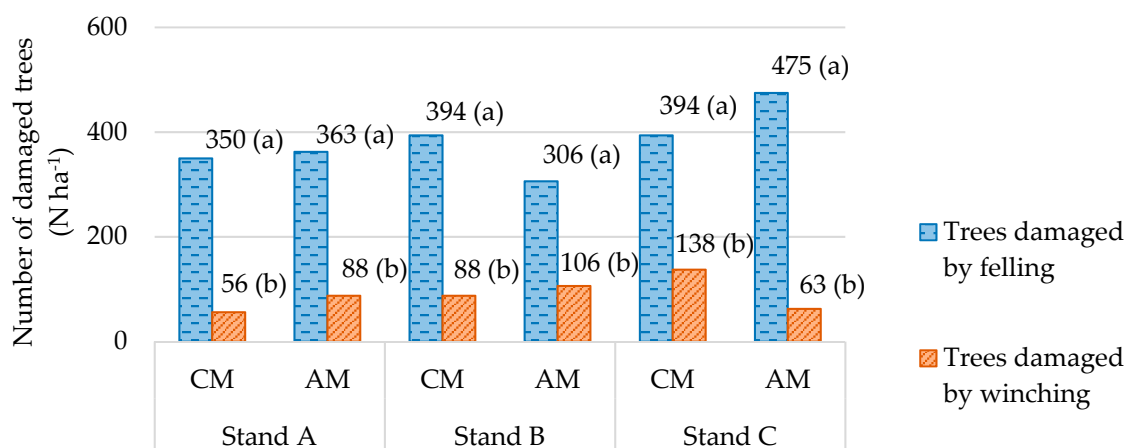
Figure 4. Harvesting damage caused by felling and winching for conventional (CM) and alternative (AM) harvesting method across stands, considering all trees with DBH ≥ 7 cm o.b. The values represent the mean values. Different letters indicate significant differences between felling and winching damage.

Additionally, different degrees of damage severity (minor, moderate, and severe) to the trees' section (crown, bole, and leaning) varied according to stand conditions. In stand A, located on steep slopes, crown damages were dominant for both harvesting methods and damaged between 20.6% (CM) and 26.5% (AM) of all remnant trees (Figure 5).
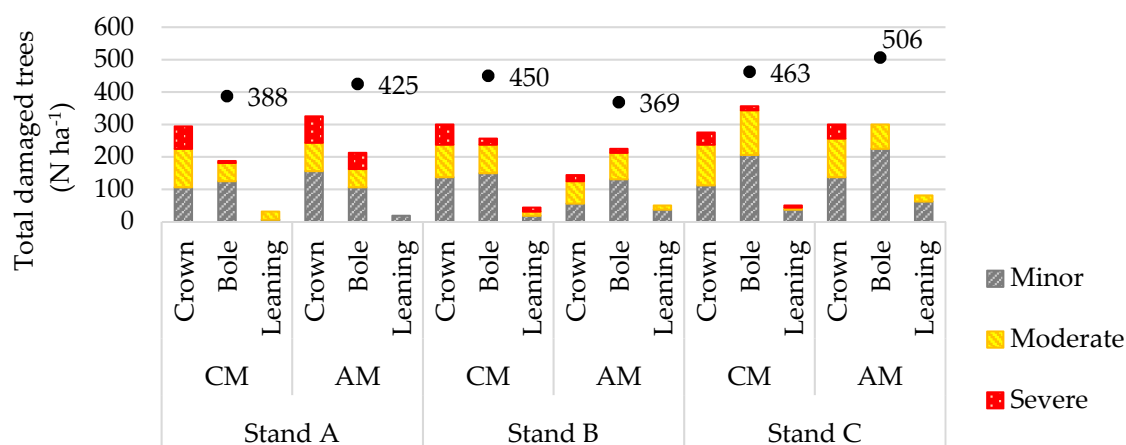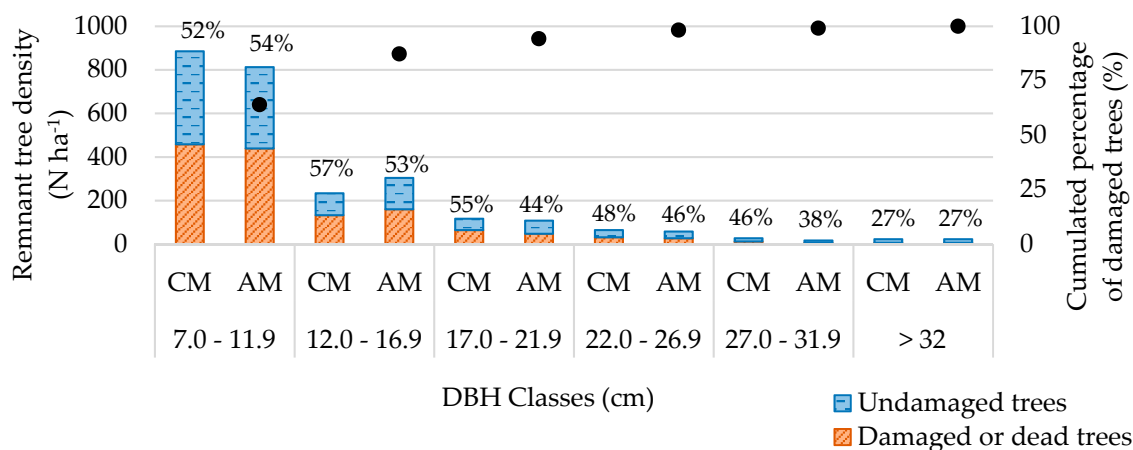

Figure 5. Number of damaged trees per damage class (crown, bole, leaning) for the conventional (CM) and the alternative (AM) harvesting method in each stand. Black dots represent the total number of damaged trees per ha. Note: a tree could belong to more than one damage category.

Noticeable is the lowest number of crown damages during AM operation in stand B (143.8 trees ha^{-1}), which represented 11.4% of the total remnant trees and, hence, resulted in a lower number of total damaged trees per hectare (368.8 trees ha^{-1}). Bole damages were also the most damaged tree section for AM in stand B and for CM in the flat terrain and dense stand C. Another important result was that for bole damages, minor intensities were prevalent across all the stands and harvesting methods. Additionally, the rate of tree leaning ranged from 2.2% (31 trees ha^{-1} in CM, stand A) to 5.5% (81 trees ha^{-1} in AM stand C) and represented the lowest observed damages on remnant trees.

Regardless of DBH class, the proportion of remnant trees damaged during the harvesting was similar for the two harvesting methods (Figure 6).

By far, the majority of damaged or dead trees (65%) were small dimensional trees with DBH ranging from 7.0 cm to 11.9 cm. However, despite the higher rates of damaged trees in the lower DBH class, small dimensional trees represented only 21% of the pre-harvest basal area and 17% of

the standing volume. Moreover, in our research, we gave special focus to harvesting damage to intermediary and higher DBH classes (above 11.9 cm DBH) (Table 5). Yet, no significant differences were found between harvesting methods, nor among stands regarding the number of damaged or dead bigger trees.

Figure 6. Harvesting damage for the conventional (CM) and the alternative (AM) harvesting methods, considering DBH classes for all tree species. Black dots represented the cumulated percentage of damaged trees related to the total number of remnant trees, for both harvesting methods. Numbers above bars represent the rates of damaged or dead trees related to the total number of remnant trees per DBH classes.

Table 5. Harvesting damage for the conventional (CM) and the alternative (AM) harvesting methods across stands considering all trees with DBH ≥ 12 cm o.b, including commercial tree species.

	Stand A		Stand B		Stand C	
	CM	**AM**	**CM**	**AM**	**CM**	**AM**
Bigger Trees (N ha^{-1})						
Remnant	462.5 [aA]	518.8 [aA]	575.0 [aA]	437.5 [aA]	493.8 [aA]	437.5 [aA]
Undamaged	237.5 [aA]	256.3 [aA]	325.0 [aA]	200.0 [aA]	225.0 [aA]	193.8 [aA]
Damaged	181.3 [aA]	200.0 [aA]	168.8 [aA]	187.5 [aA]	193.8 [aA]	200.0 [aA]
Dead	43.8 [aA]	62.5 [aA]	81.3 [aA]	50.0 [aA]	75.0 [aA]	43.8 [aA]
Bigger Trees—Basal area (m^2 ha^{-1})						
Undamaged	10.5 [aA]	11.3 [aA]	10.1 [aAB]	5.8 [aAB]	5.8 [aB]	4.8 [aB]
Damaged	5.8 [aA]	8.2 [aA]	5.9 [aA]	5.6 [aA]	4.8 [aA]	4.6 [aA]
Dead	0.9 [aA]	1.6 [aA]	1.3 [aA]	1.2 [aA]	1.4 [aA]	1.0 [aA]
Bigger Trees—Volume (m^3 ha^{-1})						
Undamaged	84.0 [aA]	89.0 [aA]	75.4 [aAB]	45.5 [aAB]	43.1 [aB]	36.9 [aB]
Damaged	43.8 [aA]	64.3 [aA]	46.1 [aA]	46.1 [aA]	34.2 [aA]	33.9 [aA]
Dead	6.1 [aA]	9.8 [aA]	9.2 [aA]	8.9 [aA]	9.5 [aA]	7.3 [aA]

Different lowercase letters in the same line indicate significant differences between harvesting methods. Different capital letters in the same line indicate significant differences among stands.

In addition, although there was a higher number of damaged trees per hectare, a lower number of damaged bigger trees (with DBH above 11.9 cm) per harvested tree was observed. In stand A, this number ranged between 1.3 trees (CM) and 2.2 trees (AM), while in stand B, it ranged between 2.5 trees (CM) and 1.7 trees (AM). Moreover, stand C, due to the predominance of low dimensional trees in this stand, showed the lowest degree of damaged bigger tree per harvested tree (0.8 trees for CM and 0.6 trees for AM).

3.3. Geo Analysis

The damage maps allowed the identification of regions of intensive damages (Figure 7). Furthermore, these maps, when combined with the mapped felling direction and the winching lines (Figure 8) allowed for a more accurate impact assessment of harvesting methods on the residual stand.
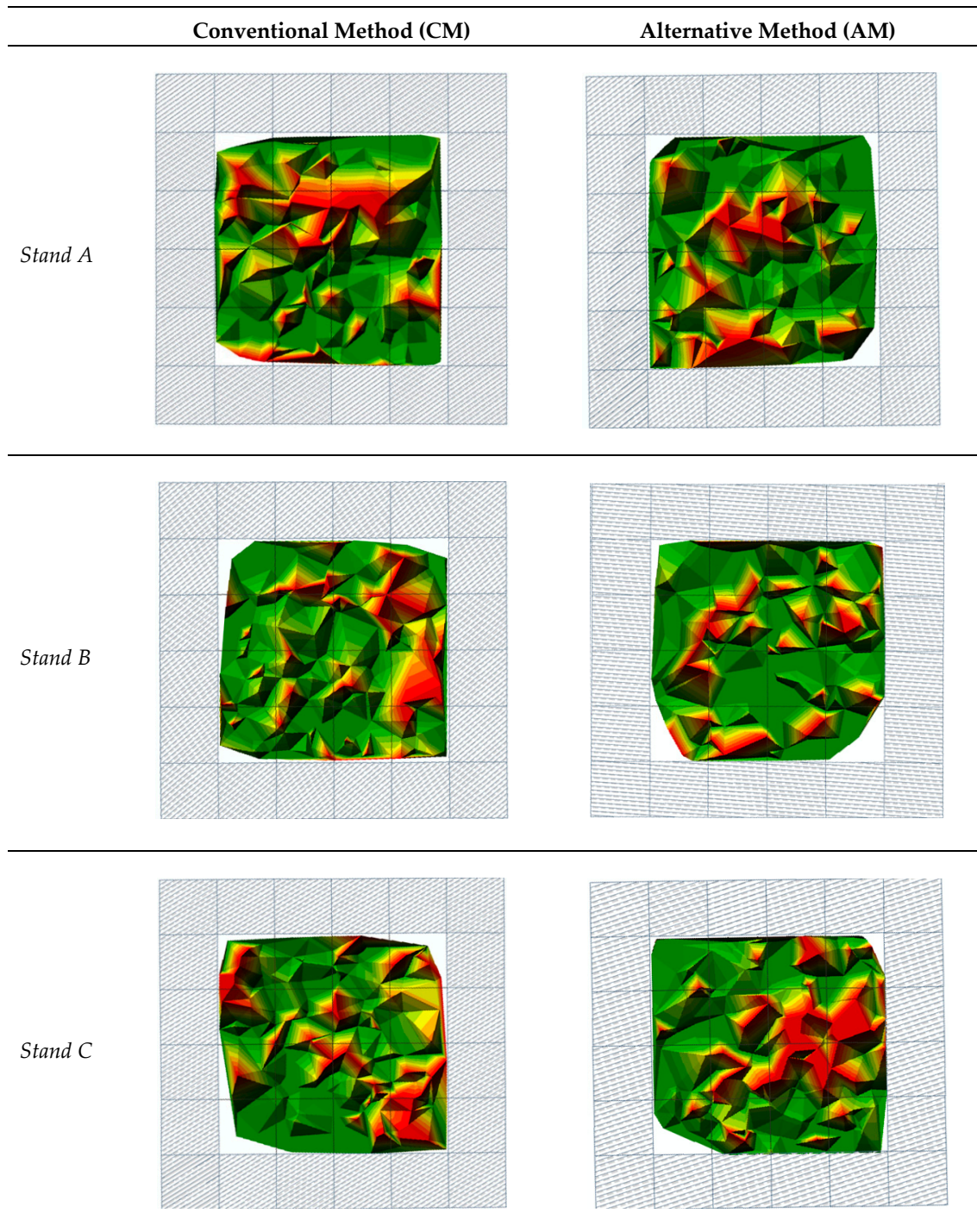

Figure 7. *Cont.*

Legend:
Damage Intensity
Severe

No damage

Buffer zone

Figure 7. Damage maps per plot and harvesting method. The damage intensities ranged from undamaged trees (green damage zones on the map) to severely damaged and dead trees (red damage zones on the map).

Most of the damaged trees were concentrated in small areas within the plots. Stand A showed a slightly larger "high damaged area" (13.8%) compared to stand B (11.1%) and yet this area was lower than for the dense stand C (15.9%). In stand A and B, the CM harvesting damaged a larger area with "high damage intensity" (234.3 m^2 and 194.5 m^2) compared to AM harvesting (206.0 m^2 and 160.0 m^2, respectively). Differently, in Stand C, CM presented a lower "high damaged area" (218.5 m^2), compared to AM (290.8 m^2) (Table 6).

Table 6. Winching distance and disturbed ground area per plot.

	Stand A		Stand B		Stand C	
	CM	**AM**	**CM**	**AM**	**CM**	**AM**
TIN Most damaged plot area (m^2)	234.3	206.0	194.5	160.5	218.5	290.8
Shortest distance from the tree location to the road (m)	32.7	29.7	26.1	23.5	21.1	12.0
Performed winching distance (m)	34.8	30.6	21.5	19.1	33.7	13.1
Estimated winching disturbed ground plot area (m^2)	200.6	140.5	105.9	113.4	184.2	72.0
Estimated winching disturbed ground area per winched tree (m^2)	100.0	54.9	60.1	47.2	60.6	18.0

Note: each research plot is 1600 m^2. No statistical test was performed for these figures given the lower number of observed winched trees, which resulted in an insufficient number of repetitions.

Spatial analysis of winching lines indicated that the winching lines did not follow the shortest extraction distance from the tree location to the road. Owing to reduced impact on the residual stand, various winching angles in relation to the road were intentionally followed during both operation methods. Yet, it is important to note that the most damaged area (red) does not correspond to the highest allocation of winching lines. The winching performed by CM caused a larger disturbed ground area in stand A (22.6%) and stand C (24.1%), compared to AM (15% and 4.5%, respectively in stand A and C). However, in stand B, with some trees felled on the tractor road, CM disturbed a smaller ground area (12.4%) compared to AM (14.5%). When looking to the disturbed ground area per winched tree, it is important to note that CM showed higher values for all three stands, compared to AM.

In addition, based on the contour lines and on the tree felling direction, most of the trees were felled following the predominant slope direction, despite the stand characteristics and slope declivity (Figure 9).

However, while for CM most of the trees were felled in a range up to 45° of the predominant slope direction, for AM, due to appropriate training courses on improved felling technique, most of the trees could be felled in a range up to 60° of the predominant slope direction.
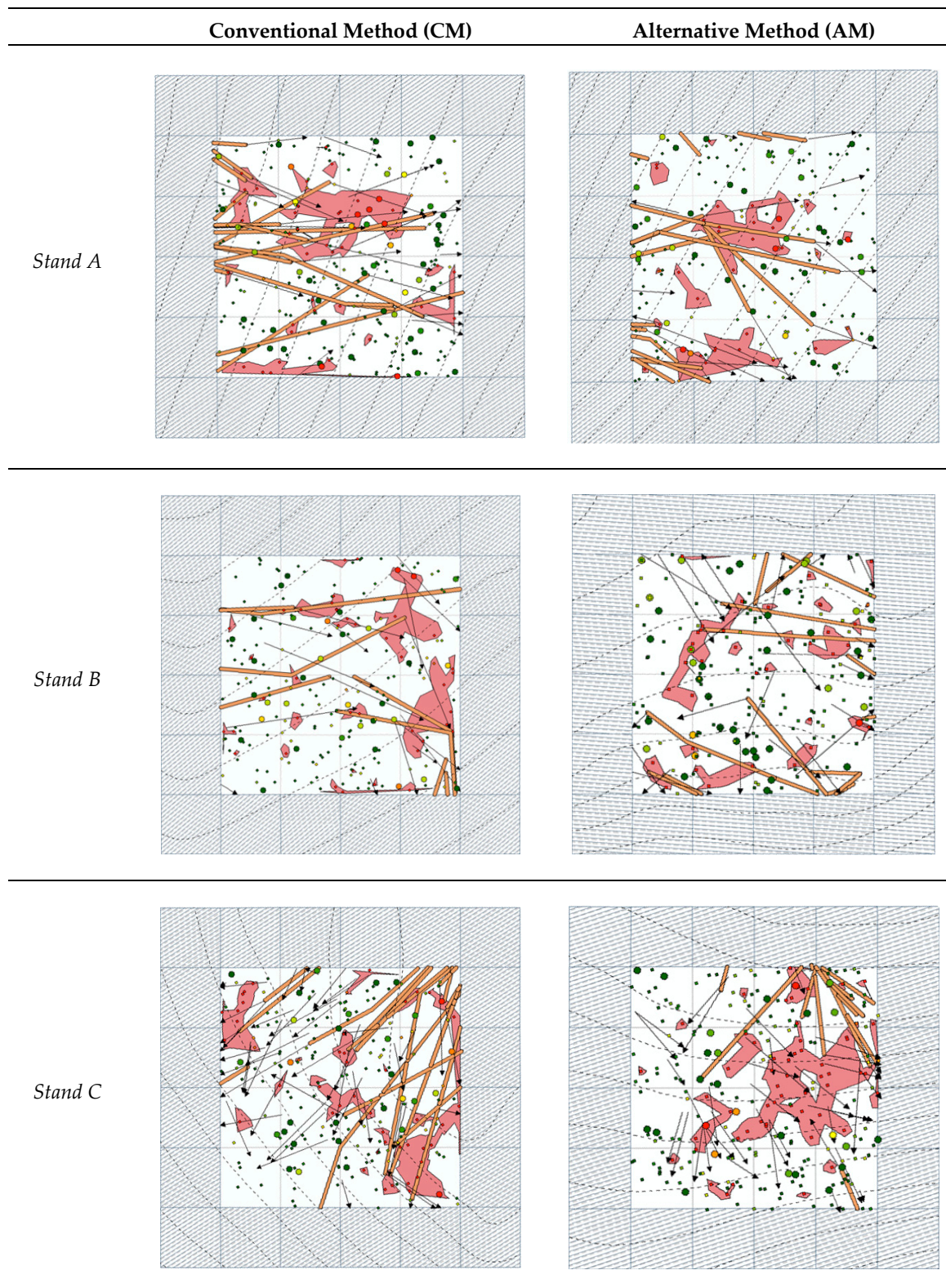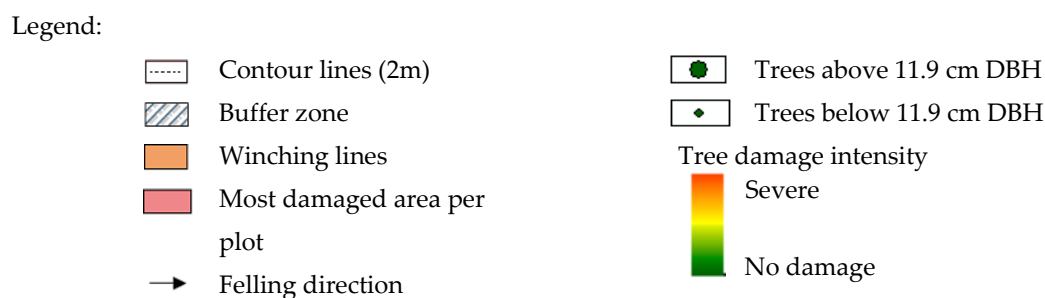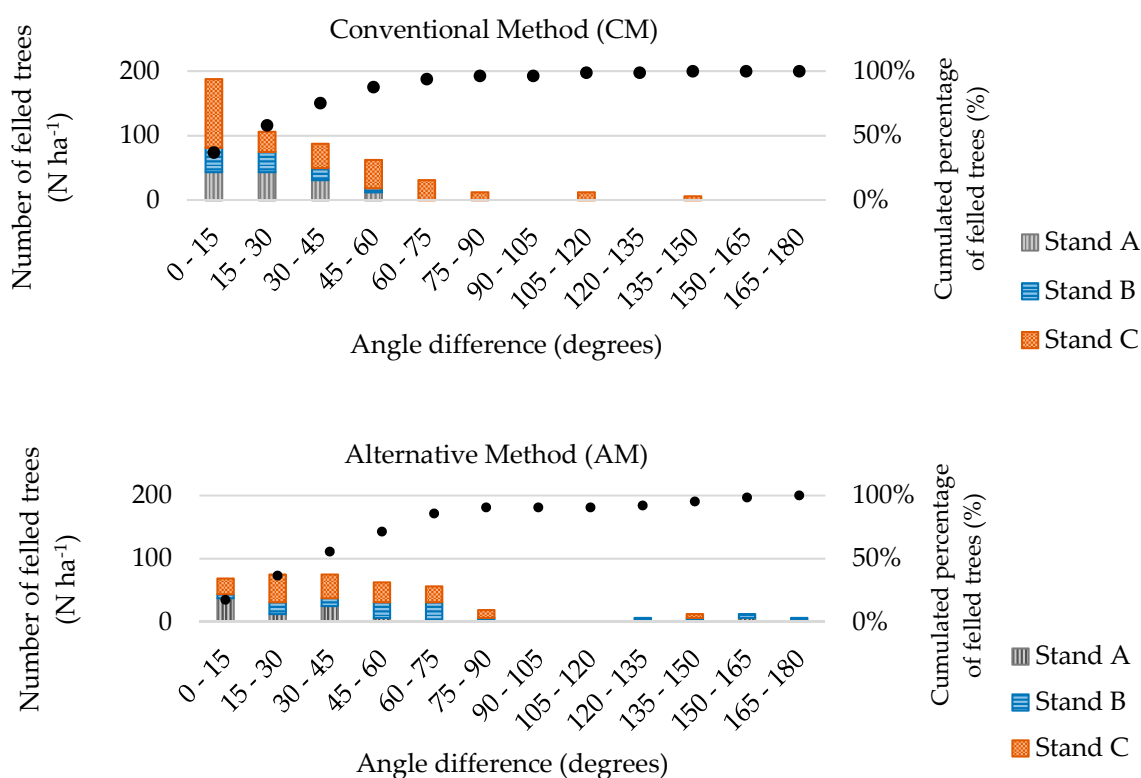
Conventional Method (CM)	Alternative Method (AM)
Stand A	
Stand B	
Stand C	

Figure 8. *Cont.*

Figure 8. Damage maps per plot with contour lines, felling direction, winching lines, and highly damaged areas (red damage zones).

Figure 9. Difference between predominant slope direction and the felling direction for the conventional method (CM) and the alternative method (AM) on the three evaluated stands.

In stand A (steep terrain), most of the trees were felled in a range up to 45° from the predominant slope direction (90% for CM and 86% for AM). Difficult terrain conditions showed a more challenging situation for both operators in order to fell a tree in a higher range of tree felling angles and consequently avoid damage on remnant trees. However, in stand B (bigger trees and more favorable terrain conditions), the AM operator could fell most of the trees (90%) in a range up to 150° from the predominant slope terrain direction. In the same stand B, the CM operator could fell most of the trees (93%) in a range of up to 45° of the predominant slope direction. In stand C, the higher number of improvement cuts associated with smaller tree dimensions did not allow any improved felling technique. Moreover, for both operators, most of the trees (89% for CM and 90% for AM) were felled in a range up to 75° from the predominant slope direction.

4. Discussion

In this study, we evaluated and compared different stand structures influencing the harvesting damages on remnant trees. Furthermore, we evaluated the harvesting impact of a "Conventional Method (CM)", compared to the harvesting impact of a proposed "Alternative Method (AM)". We assessed the impact of felling directions and winching lines by use of damage maps and compared these results with areas of high concentration of damaged trees. Furthermore, we also assessed the felling directions with respect to terrain slope.

The high heterogeneity among stands found in the studied forest (Table 2), associated with the small number of replications, limited by the available resources, represented an extra effort for the experimental layout and challenged the statistical comparison between harvesting methods. Yet, the characteristics of the studied ERF are typical for secondary forests of the region [5], and therefore, appear representative for the Atlantic Forest biome, allowing to scale up our results to other similar forests of this biome.

The characteristics of secondary forests (high heterogeneity among stands, steep slopes, and the small size of the trees) strongly limit the use of a fully mechanized harvesting system. The tree felling should preferably be performed by motor-manual felling, while the log extraction should preferably be done with cable winches. The cable winching, recommended for smaller extraction distances (up to 60 m), showed a number of advantages in our case study regarding the reduced impact on remnant trees as well as the economic viability of the system as described by Britto et al. [10]. Moreover, cable yarding could also be another option for use in a secondary Atlantic Forest and may present advantages regarding reduced harvesting impact, since the main harvesting impact would be concentrated to the yarding corridors [21]. However, it is still necessary for further research to evaluate the performance of cable yarding systems under local conditions of a secondary Atlantic Forest.

Typical for the management of a rather young secondary forest is the relative high harvesting intensity (up to 400 trees ha^{-1}) applied in this study as suggested by Silva et al. [12], as well as the small average DBH of the harvested trees, which characterize commercial thinning operations. The harvesting intensities are much higher than the intensities reported for the high forests in the Amazon with a harvesting range between 4.5 trees ha^{-1} [22] and 6.0 tree ha^{-1} [23], and a minimum harvesting DBH of 50 cm [24,25]. Furthermore, at least in mature forests of the Brazilian Amazon, harvesting has been concentrated only on large size commercial trees, while liberation and refinement thinning are not common silvicultural practices. Harvesting intensities, similar to those applied in our study, were observed only in forests with lower tree diversity and low species richness, such as temperate forests in northern Europe [26–28], or forest plantations in Southern Brazil [29]. To the best of our knowledge, there is no other research evaluating the harvesting impact of a high harvesting intensity in a hot spot biome, such as the secondary Atlantic Forest. Nevertheless, based on the positive results obtained in our research and also by Silva et al. [12] and Britto et al. [10], we believe these parameters are appropriate for the structure of the secondary forests of the region and suggest them as guidelines for tree selection in further research on the intensity of periodical harvestings in the management of secondary forests.

In stands A and B, mostly commercial tree species were harvested. Thus, the commercial harvested timber volume of stand A (74.3 m^3 ha^{-1}) and B (43.8 m^3 ha^{-1}) contributed to the economic profitability of the system and granted some economic return to the landowner, corroborating the study of Fantini et al. [8] on the potential use of secondary Atlantic Forest. In stand C, most of the harvested trees were felled for improving the residual stand. Nevertheless, this is supposed to positively influence the stand quality, and therefore, we believe this will further support the sustainable management of secondary Atlantic Forests.

In addition, it is important to point out the high rates of tree hang-ups observed during the felling for both operators in all three stands (up to 59% of the felled trees). The same is not observed in the Amazon high Forest, where the harvesting is only focused on some bigger and commercial trees [24]. However, tree hang-ups are a long-running issue in the Brazilian Atlantic Forest. Dean [30] described

that in the 19th century, for a clear cut in the ERF Atlantic Forest, tree after tree were felled against its neighbor and remained for the most part in an upright position. The author also mentioned that all trees hung-up dropped down at once when a bigger hardwood tree was felled over them, which is, of course, against common safety regulations. In our study, the higher rates of tree hang-ups were observed in stand A (54%), most likely due to the difficulties of felling a tree in a desired and adequate direction, and stand C (59%), most likely due to the very high tree density, the higher amount of improvement felling in particular of small dimensional trees. Moreover, although Britto et al. [10] suggested that the higher rates of tree hang-ups did not interfere with the productivity and costs of the evaluated harvesting methods in secondary Atlantic Forests, Albizu et al. [31] observed that one of the major causes of fatal accidents in the logging operations was the felling of hung-up trees. Therefore, special care is necessary in order to assure the safety of forest workers. The use of winching systems for cable supported felling would avoid timely and unsafe felling operations of hung-up trees.

Despite the challenging situation in the steep stand A, no effect on the rates of damaged remnant trees became obvious with respect to terrain slope or stand characteristics. Surprisingly, the steep stand A presented the lowest degrees of damaged basal area and volume compared to stands B and C. Differently, Picchio et al. [32] described that damage to the remaining stand on steep terrain can be quite severe and is usually difficult to control. These authors also showed that the share of wounded trees was directly related to slope steepness, with larger wounds on steeper slopes.

Furthermore, we did not find a statistical difference regarding the harvesting impact between the two evaluated harvesting methods. However, despite the lack of statistical proof, we observed slightly higher rates of damaged basal area and damaged volume for CM in stand A and stand B compared to AM. Moreover, in stand C, small dimensional trees at high density did not allow any improved felling techniques for a reduced impact harvesting. Additionally, it is important to mention that the AM operator was unfamiliar with the characteristics of the Atlantic Forest, particularly the composition and structure of a regional secondary forest. This indicated that the AM technique with more practice and knowledge in local conditions might achieve better results and, most likely, a lower harvesting impact. By the other side, the professional skills of the feller appointed to CM may have been underestimated. In addition, this operator had comprehensive knowledge of the local forest, was quite experienced in tree felling and, as a forest owner, was aware of the importance of reducing damage to residual trees.

Felling damages were significantly higher than those caused by winching, in both harvesting methods and in all three stands (Figure 4). The lower impact caused by winching, compared to tree felling, resulted from the planning of individual winching lines in both methods, which included extraction of logs at many different angles in relation to the road, accommodating some of the irregularities of felling directions. The existence of tractor roads at high density (81 m ha^{-1}) for easy access of the stands, an advantageous common characteristic of the small farms in the region, also helped to limit the damage to the forest stand. Furthermore, the tractor did not enter the plots, which potentially positively affected the degree of damaged trees. In contrast, Silva et al. [12] described winching and poor planning of winching lines as the main cause of damage on the residual stands in the same study area. Many other studies did not distinguish between the damages caused by the felling and extraction, reporting only the total harvesting damage [23,33,34]. Overall, our results compared to other studies, indicate that there is an opportunity to reduce the impact of harvesting in small forest farms by combining planned felling directions and winching lines.

In addition, it is important to point out that in secondary Atlantic Forests, most of the damaged or dead trees (65%) belong to the lower DBH class (from 7.0 cm to 11.9 cm), which is also described by Silva et al. [12]. However, despite the ecological importance that smaller trees and tree regeneration may have to the forest recovery, it is expected that any forest intervention may cause some damage to the remnant trees [35]. Moreover, the harvesting damage is particularly difficult to control or avoid on small dimension trees, especially in a dense tropical forest. Furthermore, the high growth rates typical for the secondary Atlantic Forest [5] might promote a faster recovery of the forest, mainly in this lower DBH class. Several studies evaluating the harvesting impact in tropical forests considered only trees

above 12.0 cm DBH [14,22,24,36]. Therefore, in our research, we also gave special focus to harvesting damage of the higher DBH classes (above 11.9 cm DBH) and we suggest our experience as a guideline for further research.

We observed that for every harvested tree, CM damaged between 0.8 tree (stand C) and 2.5 trees (stand B), while the use of AM resulted in a damage rate between 0.6 tree (stand C) and 2.2 trees (stand A) of remnant bigger trees. Nonetheless, studies conducted with RIL (reduced impact logging) techniques in tropical high forests such as the Amazon ranged from 12 to 46 damaged trees per harvested tree [22,23,36–38]. Moreover, it is important to restate the high harvesting intensities applied in our study (from 100.0 trees ha^{-1} to 400.0 trees ha^{-1}), which partially explain the higher number of total damaged trees per hectare (between 225.0 trees ha^{-1} and 268.75 trees ha^{-1}). The results contrast the much lower rate reported by Sist and Ferreira [23], of only 100 damaged tress ha^{-1} in the Amazon Forest. Although in secondary forests the average tree height is much lower than in a mature Amazonian forest, the density of considered "mature trees" available for harvesting is much higher in secondary Atlantic Forest, implying a higher total number of harvested trees and consequent damage to remnant trees.

In addition, the maps of damage intensities revealed plot areas with higher damage intensities or higher number of dead trees (red areas) during harvesting. Although the map does not show the canopy openings resulting from the felling, intensively affected areas may indicate the creation of big gaps, important to support the development of natural regeneration. However, these gaps are not homogenous and well distributed over the entire plot. On the one hand, opening a large gap can promote the growth of undesired pioneer species with no commercial interest, on the other hand; it can also promote the growth of commercial shade intolerant species. However, there is a lack of research that indicates the ideal opening size of gaps to improve the species composition or the quality of the stands, in particular for the Atlantic Forest biome. Therefore, a continuous assessment of these areas is recommended in order to verify the forest response and resilience associated with different damaged areas.

It is notable that in stand A and stand B, CM damaged a larger area with higher damage intensity compared to AM. Furthermore, the disturbed ground area by winching under CM in stand A and C was higher than under AM. We attribute the reduced area to the use of a skidding cone and a snatch block during AM harvesting. These tools enabled improved winching in AM, allowing the extraction of logs directed to the common extraction direction, for increasing variety of usable extraction corridors, and most advantageous, for using extraction corridors for several logs and consequently reducing the total stand area impacted by extraction. Picchio et al. [35] reported that the use of a snatch block reduced the damage to the residual stand and to the regeneration in small scale forest operations.

Finally, most of the harvested trees were felled following the predominant slope direction, which may also indicate the natural felling direction of each tree. However, the AM operator could fell a tree in a higher range of felling angle directions than the local CM, mainly due to the favorable conditions of stand B.

5. Conclusions

The high structural heterogeneity in unmanaged secondary forests is noticeable, even in such small research areas. This result is important in itself, as it reinforces the statement that the secondary forest of the region forms a mosaic of small patches with particular site conditions, as well as the forest composition and structure. Nevertheless, the high stand heterogeneity required extra effort to fully understand and challenged the assurance of comparability between harvesting methods and stands. Hence, no statistical difference was observed with respect to the harvesting damage on remnant trees between the two evaluated harvesting methods and three stands.

Our results bring new insights on the impact of harvesting on residual stands of secondary forests in the Atlantic Forest biome. Our results suggest that small improvements, like the use of extraction tools and increasing the chainsaw operator's skill, can significantly reduce damage to residual trees.

However, further research is necessary to evaluate more options for forest harvesting such as the use of cable yarding or cable supported felling techniques. The high stand density of these forests, frequently not subjected to silvicultural treatments, may limit the effectiveness of the efforts to reduce harvesting damage. Future studies should further address this issue in particular.

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