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Chapter

Damaged Trees Caused by Selective Thinning in Two Tropical Mountain Rain Forest Types in Southern Ecuador

Omar Cabrera, Pablo Ramón, Bernd Stimm, Sven Gunter and Reinhard Mosandl

Abstract

The proportion of damaged trees and the type caused by the selective thinning can have serious impacts on the ecological and economic sustainability of forests. So far, the damage caused by thinning operations in montane tropical forests is unknown. In this study, we try to quantify the damages caused by selective thinning in two types of humid montane forests in southern Ecuador. For this, we installed 52 permanent plots of 50 m x 50 m in two force types. In the valley forest (VF), we extracted an average basal area of 2.75 m² ha^{-1}, in the ridge forest (RF) an average basal area of 0.8 m² ha^{-1} was extracted. For each felled tree, we counted and categorized the damage separated by large (>20cm DBH) and small (<20cm DBH) residual trees. Using a generalized linear model (GLM) we could determine that the diameter of the felled tree significantly influences the number of large as well as small trees temporarily or permanently damaged. Basal area thinned in the VF significantly influenced the proportion of trees < 20 cm DBH affected by Permanente Damage (PD) and Temporal Damage (TD). In the RF, the crown area of felled trees influences the proportion of (PD) trees with DBH > 20 cm. The extracted basal area significantly influences the proportion of (TD) trees with DBH < 20 cm. In general, the proportion of temporarily damaged (TD) trees is greater than the proportion of permanently damaged (PD) trees in both types of forest. Considering only the heavily damaged trees we can conclude that the damage in total is acceptable.

Keywords: tropical mountain rain forest, sustainable forest management, selective thinning, damage type and probability

1. Introduction

Currently, sustainable forest management (SFM) practices in some tropical forests are poorly implemented for several reasons, including high cost, lack of government

incentives to promote sustainable practices, conversion of exploited (unmanaged) forests into pastures, and land for agriculture between others [1, 2].

Some SFM practices include activities, new methods, and technology development for the sustainable use of forest resources and to minimize any negative impact on the environment [3]. Within these activities and as an important component to achieve ecological sustainability, thinning and harvesting operations must be planned to avoid the negative impact of forestry operations on the soil, on regeneration, and on the residual mass [3, 4].

Activities such as directed felling and optimized skidding methods have shown that the percentage to remaining forest has decreased [5]. We should also mention that the size of felled trees and the size of residual trees affect the amount and types of damage to residual trees, i.e., larger felled trees cause more damage to residual trees [6, 7].

To make SFM compatible with biodiversity conservation, the impact of these activities on the remaining forest must be evaluated. The damage caused by felling and thinning on residual trees should be considered one of the fundamental factors to assess the sustainability of forest management. Nevertheless, no study has predicted different degrees of logging damage with consideration of the size of both residual and felled trees simultaneously for tropical forests [8].

General damage (severe or light) caused to residual trees could jeopardize the goal of selective thinning and show a higher probability of mortality for severely damaged trees [9]. In some cases, thinning logging damage to residual trees can result in their death, and the frequency of wounded trees and severity of wounds during logging operations may have detrimental impacts on stand growth and forest sustainability [10].

In order to know the magnitude in which the mechanical damage caused by selective thinning affects the remaining forest, it is necessary to determine the levels of damage that could be determined as indicators of the intensity of thinning and exploitation [11, 12] in large forest concessions as well as on private farms to minimize the impacts of thinning and ensure that it is included as a good SFM practices [13].

Another consequence of implementing selective thinning is the opening canopy; in forests, without intervention the fall of old trees naturally produces clearings and this process allows the renewal of tree populations [14, 15]. On the other hand, the intensity and frequency of the intervention are factors that influence the structure and composition of the species that colonize the gaps.

Authors like [16] determined that the intensity of intervention and the different silvicultural treatments have a significant impact on the density and growth of regeneration as well as saplings and seedlings of timber species. The loss of diversity [17] and number of individuals decrease due to post-disturbance mortality and its limited recruitment, and Dickinson et al. [18] state that the gaps produced naturally and those produced by the effect of the intervention have different disturbance conditions, with natural gaps favorable for the colonization of shade-tolerant species. Under the previous premises, we consider that the impact of selective thinning on natural regeneration must be monitored [19], with natural regeneration being a factor that has always been a bottleneck for foresters in tropical forests.

In several neotropical countries, forestry activities have been implemented to reduce the negative effects of harvesting and treatments to improve forest conditions. Reduced impact logging (RIL) includes pre- and post-activities that minimize unnecessary damage to remnant forest and soil [1]. Under this framework in Ecuador, the norms to regulate the use and management of forests are relatively new (approximately since 2001). They briefly mention the activities that promote sustainable forest

management and use. All efforts to develop sustainable forest management practices focus on issues related to the felling and use of forests, ecosystem services, and forest plantations, but silvicultural experiments have not been carried out to evaluate the effectiveness, for example, selective thinning for the production of wood in natural forests and the impact or damage to the remaining forest that they produce, considering that this process is a fundamental element to assess the sustainability of both thinning and logging of the forest [8].

The purpose of this study is to evaluate the type and extent of mechanical damage caused by the fall of thinned trees over the remaining forest. The hypothesis that we propose to develop the work are as follows: (i) the damage type of residual trees is correlated with the intensity of thinning; (ii) the number and size of affected trees is related to the DBH of felled trees and the total basal area extracted; and (iii) the structure and spatial distribution of the residual forest determine the types of damage and number of trees affected by the felling operation.

2. Materials and methods

2.1 Study area and biophysical conditions

The study was carried out in the San Francisco Biologic Reserve (ECSF), which is located at 03°58′ S, 79°04′ W, 1850 m a.s.l. [20], i.e., north of Podocarpus National Park (PNP) in Southern Ecuador. ECSF is situated within the eastern cordillera of the Andes [21]. A comprehensive and detailed description of the San Francisco Reserve and its surroundings can be found in [22], which also detail a series of the research activities in this tropical mountain forest and present the different experiments conceived with the purpose of knowing the functionality and management of the forest. Refs. [23, 24] found a description of the scope and achievements of the forestry project installed in the ECSF.

2.2 Plot installation

Fifty-two plots of 2500 m^2 were installed in ECSF and located in three sites (quebradas) named Q2-Q3-Q5 at different altitudes. Authors like [25, 26] determined several forest types covering the ECSF. Installed plots were grouped and floristically ordered in two forest types. The first group called valley forest (VF) is characterized by the presence of *Tabebuia chrysantha* (Jacq.) G. Nicholson, *Cedrela montana* Moritz ex Turcz., *Inga acreana* Harms., and *Ficus citrifolia* Mill. These species are involved in the application of selective thinning, and ridge forest (RF) that is characterized by the presence of *Podocarpus oleifolius* D. Don ex Lamb., *Hyeronima moritziana* Mull. Arg, *Clusia ducuoides* Engl. which are released species. In Q2 (control block), we installed 20 plots (6 plots in RF and 14 plots in VF), in Q3 (only RF) we installed 16 plots, and in Q5 (only VF) we installed 16 plots (**Figure 1**). To implement the selective thinning (n = 30), we used only the plots installed in Q3 and Q5.

2.3 Thinning intensity

In VF plots, an average of 24.6 ± 0.66 stems ha^{-1} was extracted. The lowest value was 8 trees ha^{-1} and the highest value was 56 trees ha^{-1}, the basal area extracted is = 2.75 m^2 ± 1.1 ha^{-1}, and the highest extraction intensity is 4.8 m^2 ha^{-1}. In RF, an

average of = 9.67 ± 0.44 trees ha^{-1} was extracted. The lowest value was 4 trees ha^{-1}, the highest value was 24 trees ha^{-1}, the average basal area extracted was 0.89 m^2 ± 0.1 ha^{-1}, and the highest extraction intensity was 1.1–2 m^2 ha^{-1}, and the remaining plots are control without extraction.

In VF, the diameter of the felled trees ranged from 14.8 to 61.7 cm DBH (n = 97). In RF, the diameter of the felled trees ranged from 10.2 to 60 cm DBH (n = 60); in classes V and VI, there were no cut trees. The next table shows the number of felled trees in each forest type. The entire thinning operation was carried out under the condition of directional felling in order to minimize damage to residual trees (**Table 1**).

2.4 Assessing damages to residual trees caused by selective thinning

Immediately after the implementation of selective thinning in both forest types (16 plots in VF and 14 plots in RF), the number of damaged trees and the damage type caused by felled trees on residual large and small trees were monitored. We did not discriminate between trees affected by the trunk or by the crown of the felled tree; we only counted the trees affected by both sections. A separation of the damages caused by the felling of the trees and those caused by dragging the trunks out of the forest was not necessary, because in our case, we did not remove the fallen trunks and they were left inside the forest.
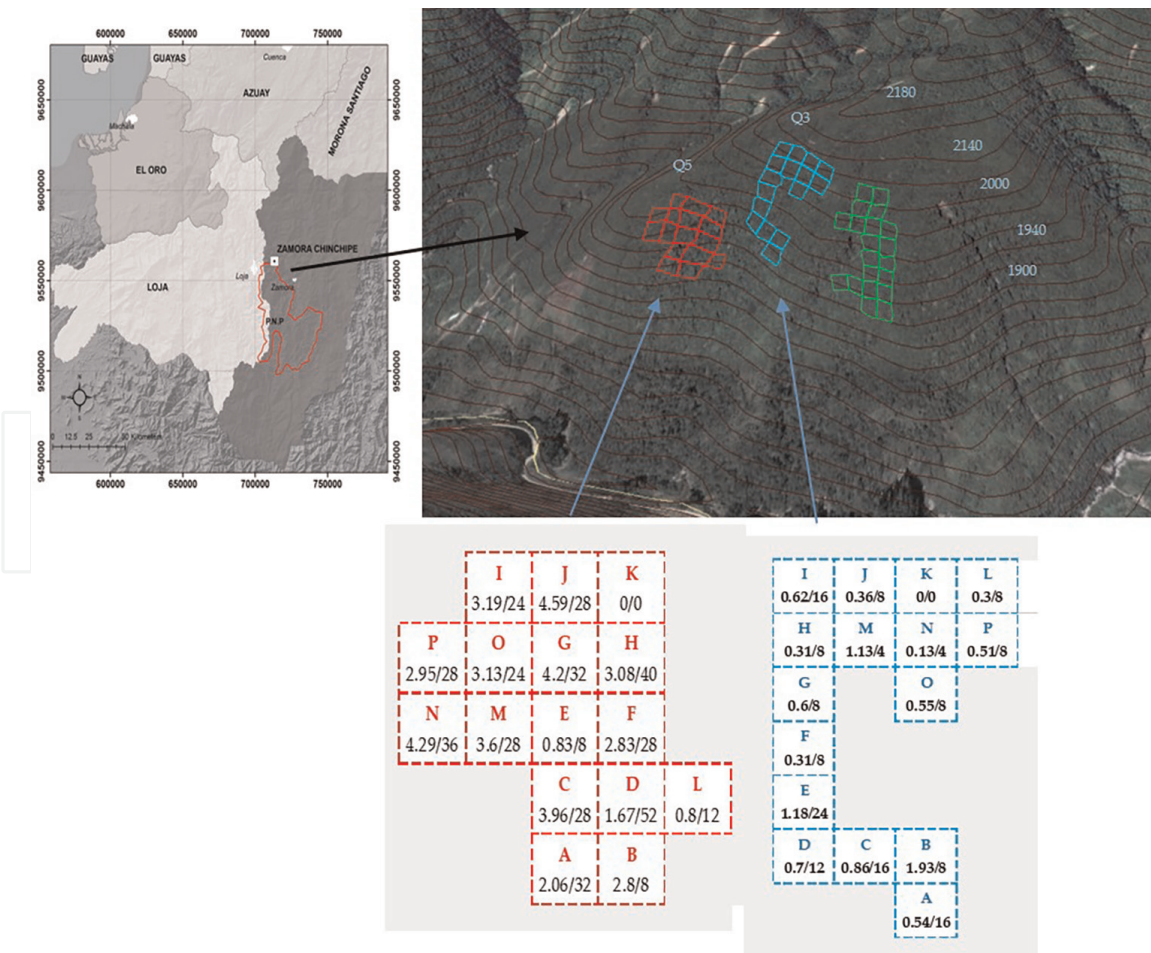

Figure 1.
Location of study area. The diagram shows the plots of each block and the internal numbers show the extracted basal area and the number of trees cut/ha^{-1}.

Damaged trees were classified according to their size in small trees (up to 20 cm DBH) and big trees (>20 cm DBH) trees. The damage was categorized as temporary (TD) when the trees were moved from their original position but were not uprooted, when branches were broken or the bark of the trunk was removed by the falling tree. The damage was described as permanent damage (PD) when trees were uprooted or their trunk was broken.

2.5 Assessing damages to residual trees caused by selective thinning

After counting the damaged large and small trees and determining the type of damage, we proceeded to calculate the proportion of damaged trees in each of the different diameter classes (large and small trees; permanent damage and temporal damage). The calculation of the proportion allows us to include in the evaluation model other parameters that are related to the structure of the residual forest. For each felled tree, the proportion of damaged residual trees was calculated using the following formula:

Proportion of trees temporarily damaged:

$$P_{Temp} = \frac{X_{ic}}{N_c} \tag{1}$$

X_{ic}: affected trees by the felled tree in class c

N_c: total trees belonging to diametric class c (>20 cm, <20 cm DBH).

This proportion was computed in both forest types (ridge forest and valley forest). The same was done for permanent damages too.

To evaluate the effect of the variables on the variability of the proportion of damage on the residual trees, we fit generalized linear models (GLMs) of the binomial family. Such models are appropriate for binary or proportional data. Significant effects were elucidated at the alpha = 0.05 level. All calculations were performed in R version 3.6.3 (R 2020 core development team). **Table 2** summarizes the predictor and response variables involved in the model.

3. Results

A total of 157 trees were thinned, 97 in VF and 60 in RF. In the plots that belong to the VF, we found $\bar{X}$ = 285.4 ± 46.7 SD trees > 20 cm DBH and $\bar{X}$ = 1084.6 ± 390.4 SD trees < 20 cm DBH. In the RF plots, we found $\bar{X}$ = 157.6 ± 40.6 SD trees > 20 cm DBH and $\bar{X}$ = 1717.1 ± 390.6 SD trees < 20 cm DBH. These results are important because

Forest type	Diametric classes (cm)						Total
	I (10.1–20)	II (20.1–30)	III (30.1–40)	IV (40.1–50)	V (50.1–60)	VI (>60)	
Valley forest	7	45	27	10	7	1	97
Ridge forest	24	26	9	1			60
							157

Table 1.
Number of thinned trees for each diametric class in both types of forest.

Variables	Description	Type	Factor scales
DBH	DBH of felled tree	Predictive	cm
Tree density	Trees/ha in each 2500 m^2 plots (50 m × 50 m) where selective thinning was implemented	Predictive	Trees/ha
Basal area	Basal area extracted/ha	Predictive	m^2/ha
Crown area	Crown area of each of the felled trees.	Predictive	m^2-m^2/ha
Proportion of damaged trees < 20 cm	Proportion of trees temporarily or permanently damaged by the implementation of selective thinning with respect to total trees of sample plot	Response	Rate of damaged trees
Proportion of damaged trees > 20 cm	Proportion of trees temporarily or permanently damaged by the implementation of selective thinning with respect to total trees of sample plot	Response	Rate of damaged trees

Table 2.
Variables that were used to model the GLM.

the numbers of large and small trees making up the structure of each forest are key variables to estimate the amount of damage of residual trees.

A total of 1061 affected trees were monitored, 710 trees in VF and 351 in RF. In the VF, 457 trees were damaged temporarily (>5 cm DBH: n = 252; <5 cm DBH: n = 205) and 253 trees had a permanent damage (>5 cm DBH: n = 92 and <5 cm DBH: n = 161). In the RF, 239 trees with temporary damage were observed (> 5 cm DBH: n = 139; < 5 cm DBH: n = 100) and with 112 trees had a permanent damage (> 5 cm DBH: n = 53; < 5 cm DBH: n = 59).

3.1 Assessing the damages

In both forest types, TD were higher than PD as well in large as in small trees. In both forest types, permanent damages are higher in large trees than in small trees, the difference being more pronounced in the RF. In both forest types, the mechanical damage pattern can be explained. When directional felling was applied, it was paid attention that medium and large trees (in this study trees > 20 cm DBH) were not affected. These trees were better visible than the smaller ones (< 20 cm DBH) (**Figure 2**).

Regarding the damage rates related to the size of the thinned tree in trees >20 cm DBH and trees <20 cm DBH, the TD rate is higher than the PD rate. Trees felled within class III are those that cause the highest TD and PD damage rates. The felled trees of the larger diameter classes are less frequent in the thinning, since they generally reach upper canopy strata and do not affect the trees of the middle strata where the released trees are located (**Figure 3a**). As for small trees, the pattern is the same; that is, thinned trees belonging to diameter class III are those that present the highest rate of TD inflicted on residual trees (**Figure 3b**).

In VF, felled trees of diameter classes IV–V are the ones that produce the highest rates of TD and PD in large (**Figure 4a**) and small (**Figure 4b**) trees. As in the previous forest, the felled trees of the smaller classes produce a lower damage rate, while the larger trees cause TD and PD at a higher rate. The implementation of selective thinning implies the release of trees mainly from classes II–IV, and the competitors are pigeonholed in the same diameter classes and are the most visible at the time of planning the directed felling.
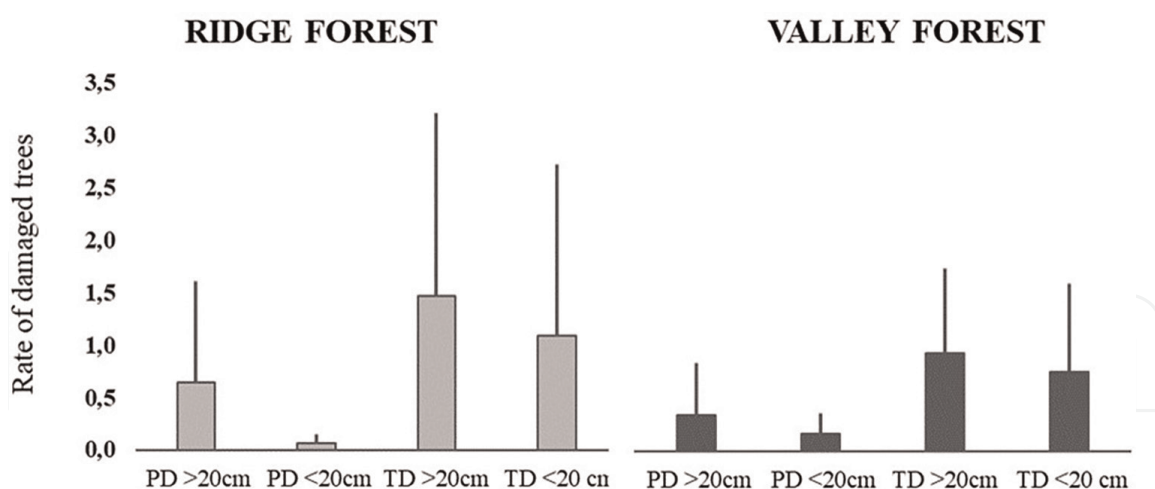
Figure 2.
Average rate of TD and PD in large and small trees in the two forest types (RF and VF). The lines above the bars represent the standard deviation.

3.2 Tree damage proportion

The proportion of total damage is significantly related to the diameter of the felled tree in the VF (p = <0.0001, **Figure 5a**) and in RF (p = <0.0001, **Figure 5b**). In the VF, the proportion of damaged trees is significantly related to the diameter of the extracted tree and to the total basal area extracted, which also significantly influences the proportion of trees permanently damaged < 20 cm DBH (p = 0.0059) and affected with temporary damage < 20 cm DBH (p = 0.001) (**Table 3**).

In the RF, the proportion of damaged trees is significantly related to the diameter of the harvested tree and the total basal area harvested, which also significantly influences the proportion of temporarily damaged trees < 20 cm DBH (p = 0.005), and the proportion of trees with permanent damage >20 cm DBH is also influenced by the crown area of the felled tree (p = 0.006) (**Table 4**).

4. Discussion

The implementation of activities to improve the performance of natural forests and the effects of harvesting wood also directly affect the residual stand. Knowing the number of trees affected and the type of affectation suffered by the residual stand are two important parameters that will allow better management of natural forests [5].

The relationship that exists between the volume of wood harvested, the size (mainly DBH expressed in basal area), the number and type of damage to residual trees plus the harvesting system (traditional vs. reduced impact logging) have been monitored for some time and in some types of forest [27–29]; however, the impact produced, for example, by selective thinning as an activity to improve forest yield is less known and documented, especially in neotropical countries where sustainable forest management practices, although regulated and mandatory, have not been monitored and evaluated, which has resulted in small- and medium-sized areas (< 50 ha) where the forest has been exploited and degraded.
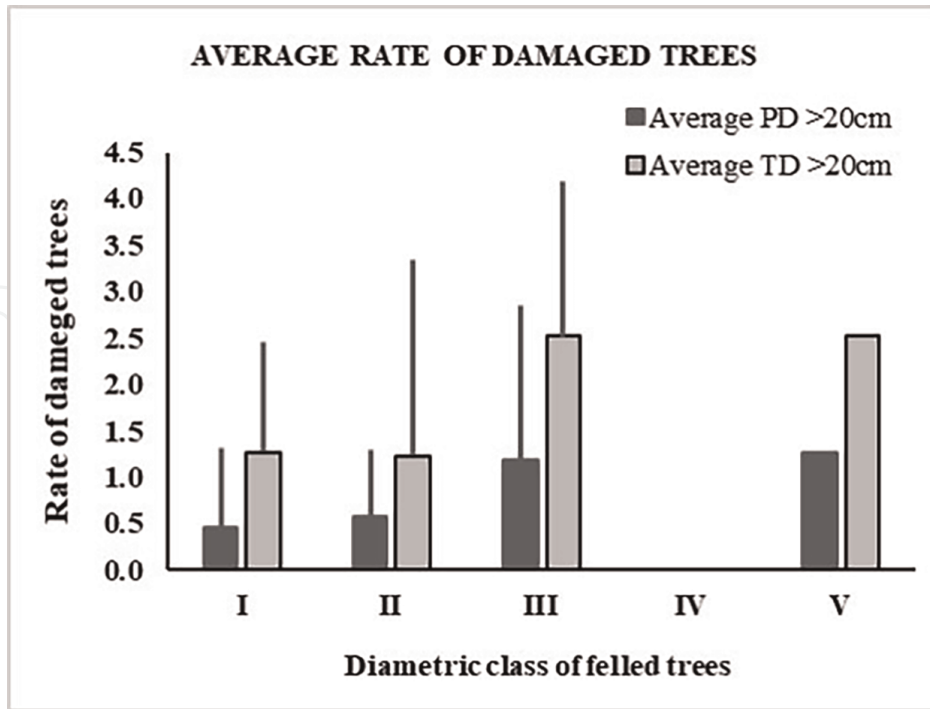
(a)
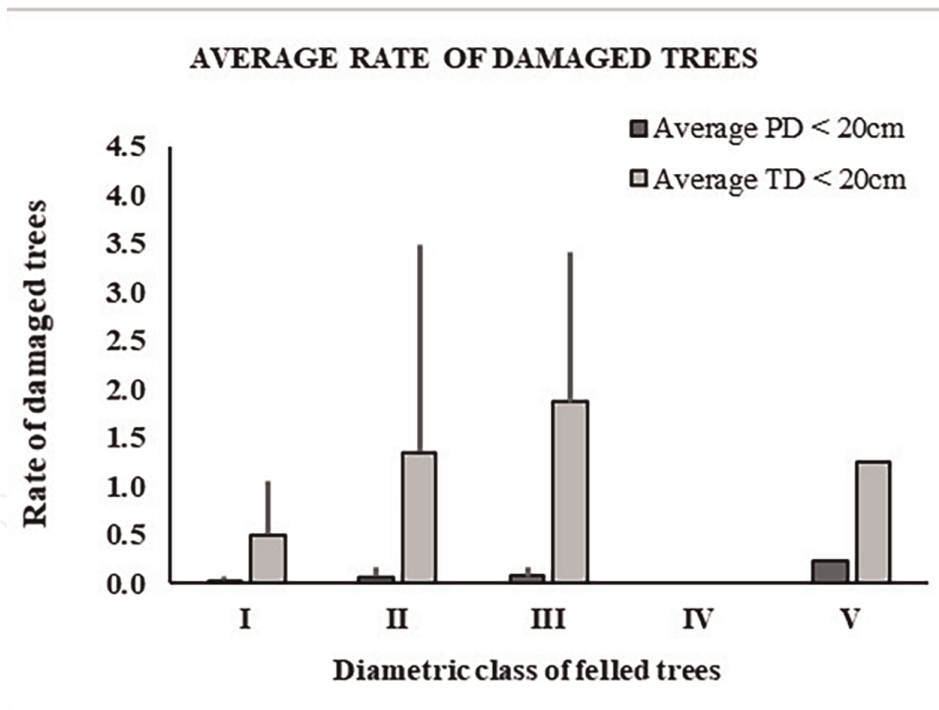
(b)

Figure 3.
TD and PD rates of big and small residuals trees in RF.

4.1 Mechanical damage

In Ref. [30], an average of 6.3 trees ha^{-1} (3.4 m^2 ha^{-1}) was extracted; however, the variation was much higher (up to 9.6 m^2 ha^{-1} in some plots) and the values of affected trees were greater than those reported in our study (15.6 ± 8.3 vs. 31). However, the aforementioned authors correlate in a positive and significant way the number of trees
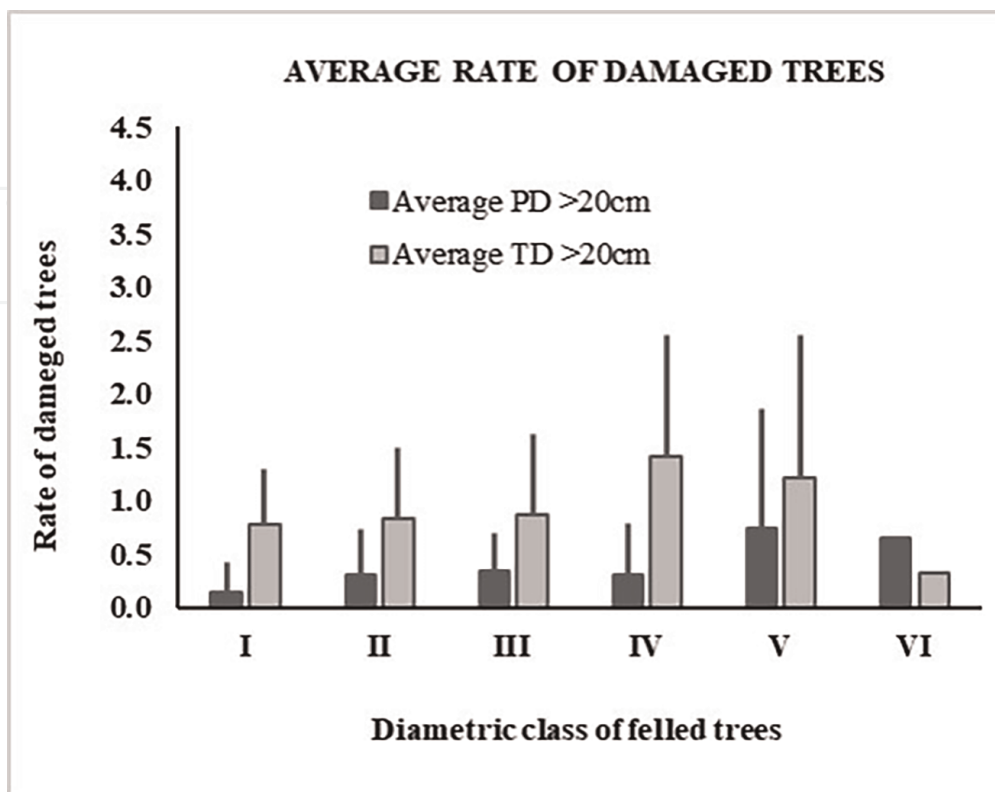
(a)
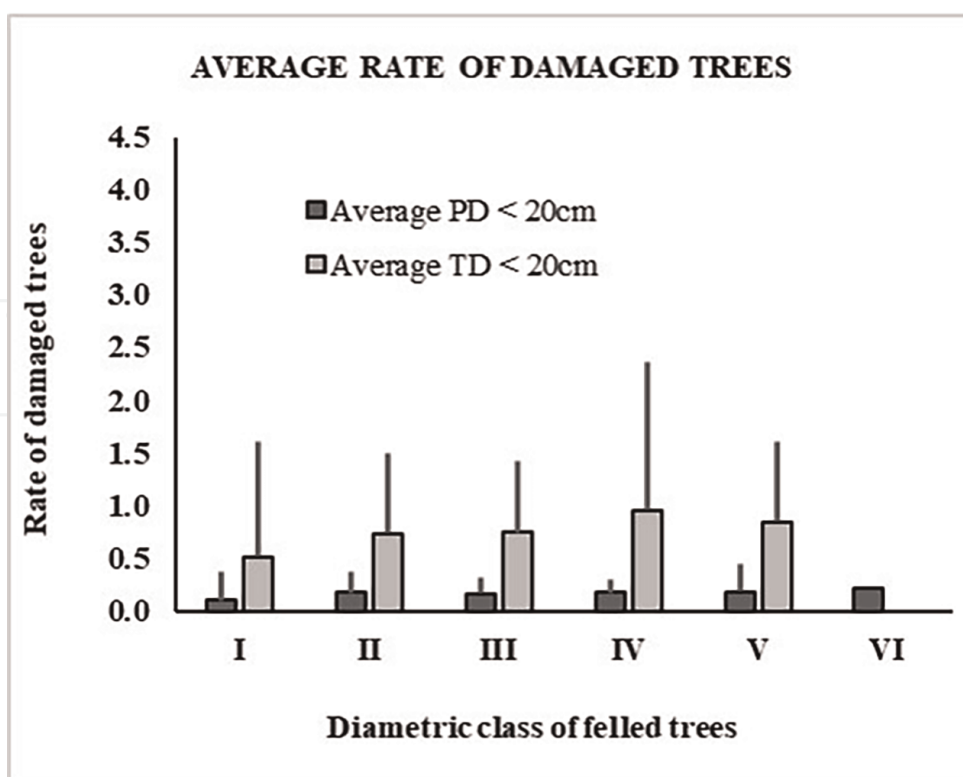
(b)

Figure 4.
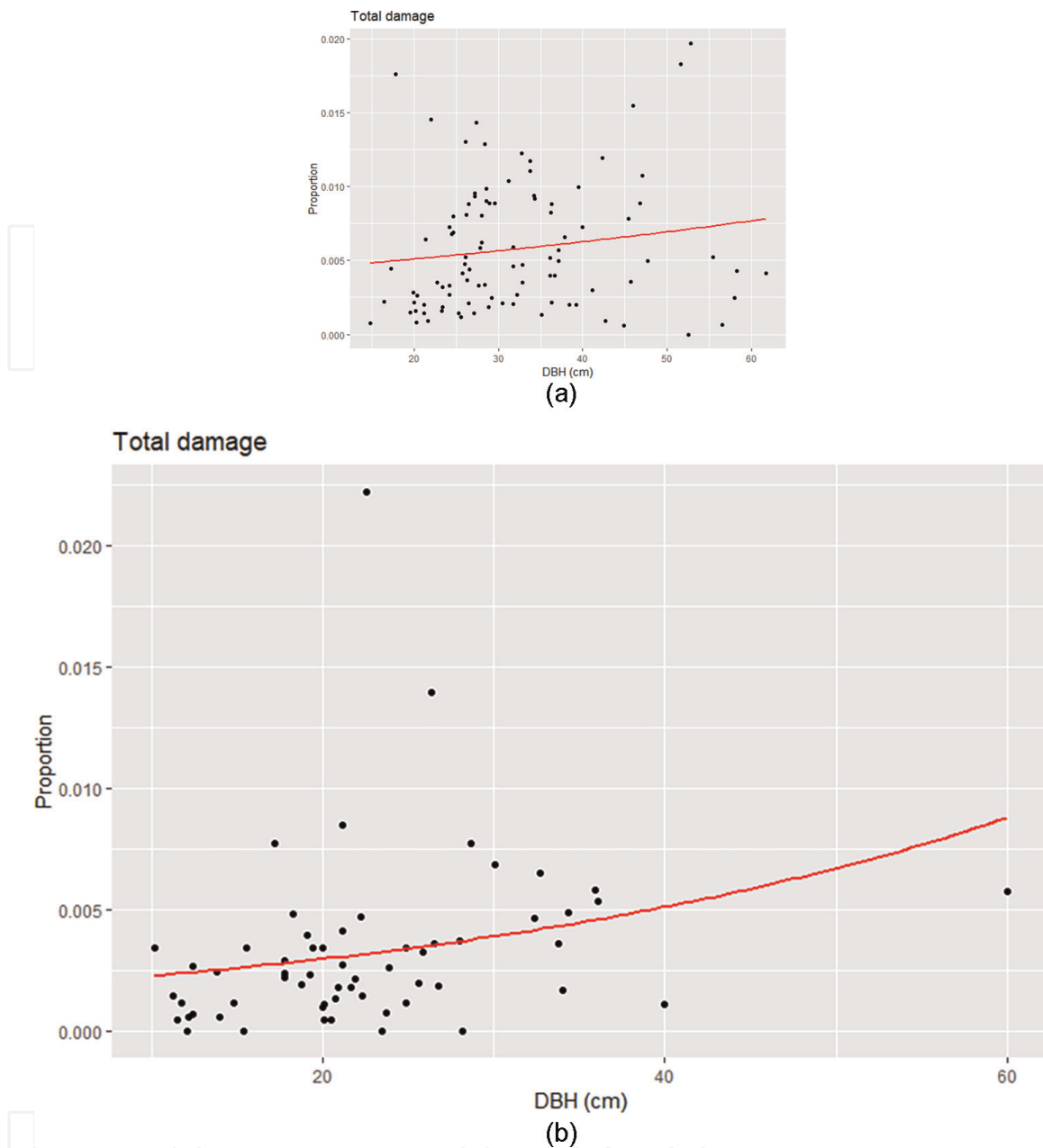*TD and PD rates in big and small residual trees of VF.*

Figure 5.
Damaged trees by DBH of felled trees. The lines show a significant correlation (p = 0.05).

harvested with the number of trees destroyed and the number of damaged trees; in this case, the damaged trees correspond to the TD type and the trees destroyed correspond to the PD type.

Regarding the type of damage suffered by trees in the remaining forest [27] determined six damage types, of which four classes are evaluated in this work, and which can be included within the categories of damage that we determine here (e.g., damage in the bark and damage in the crown of the trees can be equated in the category of temporary and permanent damage, respectively). The most frequent type of damage reported by Ref. [27] is the damage to tree crowns and also uprooted trees both on the trawl roads and in the gaps within the forest, while in our study the damage more frequently in both intensities of thinning is broken trunk, uprooted trees in our evaluation represent between 10 and 20% of the total trees affected in both intensities of thinning; in the same study, the percentage represents between 15

Source of variation	Estimate	Standard error	P	
Permanent damage (DBH > 20 cm)				
DBH	0.024	0.0089	0.00729	**
Permanent damage (DBH < 20 cm)				
DBH	0.154	0.0523	0.00314	**
Basal area extracted	−24.644	89.517	0.00590	**
Temporal damage (DBH > 20 cm)				
DBH	0.014	0.0056	0.00932	**
Temporal damage (DBH < 20 cm)				
DBH	0.113	0.0449	0.0121	*
Basal area extracted	−18.352	77.241	0.0175	*
Total damage				
DBH	0.112	0.0237	< 0.0001	***
Basal area extracted	−16.849	40.131	< 0.0001	***

DBH: diameter at breast height, BA: basal area.
*0.05.**0.05.***<0.001.

Table 3.
Summary table of the binomial GLM, for permanent, temporal, and total damage to trees of different diameter class in VF.

Source of variation	Estimate	SE	P	
Permanent damage (DBH > 20 cm)				
DBH	0.0353	0.0124	0.0044	**
Crown area	0.0154	0.0057	0.0067	**
Permanent damage (DBH < 20 cm)				
DBH	0.0403	0.0105	0.0001	***
Temporal damage (DBH > 20 cm)				
DBH	0.0185	0.0082	0.0247	*
Temporal damage (DBH < 20 cm)				
DBH	0.1754	0.0499	0.0004	***
Basal area extracted	−297.217	106.027	0.0050	**
Total damage				
DBH	0.09136	0.0215	< 0.0001	***
Basal area extracted	−122.738	41.269	0.0029	**

DBH: diameter at breast height, BA: basal area, CA: crown area.
*0.05.**0.05.***<0.001.

Table 4.
Summary table of the binomial GLM, for permanent, temporal, and total damage to trees of different diameter class in RF.

and 30% in all the scenarios evaluated. Regarding the number of individuals affected by type of damage, the average values in VF range from 1 to 9 uprooted trees and in RF, it ranges between 0.99 and 2 uprooted trees, values much lower than those reported in the mentioned study.

Despite the fact that there is evidence to suggest that the ecological impact of felled, or lying trees, have the so-called competitors, the actual values show a decrease with respect to those obtained by Veríssimo [31], who determined that in a forest in the Brazilian Amazon for every tree harvested, and there were 23 trees over 10 cm DBH, which were severely damaged. However, this includes openings in the road for hauling. Likewise, Johns [5] evaluated an unplanned method of harvesting trees. Their study found that severely damaged conditions led to significant differences between the planned and unplanned operation (7.4 vs. 4.5 trees / tree lying).

On the other hand, Abebe and Holm [32] evaluated the effect of selective harvesting on residual stand by classifying the type of damage in three categories, which according to [33] show a slight modification: damage type I or slight damage, damage type II (defined as injury in the trunk surface or more than 2 m long, or affecting 20% of the circumference, or a broken tree crown of over two-thirds), and finally damage type III, which is when the tree is broken.

It was determined that an average of 8 trees > 5 cm DBH per lying tree was damaged during the fall. Sixty-two percent of all damaged trees were broken. And, compared with our study, this result can be equated with PD, which does not equate the percentage or number of trees and the way they died—this being a parameter with which no information could be found for evaluation and comparison.

It was observed that in the two sites, damage percentages have values in the three forms of mortality assessed. In RF plots, the highest value corresponds to broken trees, while the values of the other two forms have similar values (9.8 and 8.9 dead standing and uprooting). In RF plots, the values of uprooting and standing dead have the same values (20.1 and 21.5). In VF plots, the values of uprooting and dead standing show a double percentage of occurrences in RF plots, which is calculated by determining the difference of large trees that exist between both sites.

Ref. [11] indicates that the damage produced by the effect of harvesting and selective felling depends on many factors including some that we have analyzed in this first part of the discussion; among them (those studied here) are the size of the tree lying down, the implementation or not of directed fall, the intensity in this case of selective thinning, even though the values and percentages of damage reported in the literature are very variable and recommend to indicate the type of damage as an important factor in the evaluation of the sustainability of forest operations.

Comparing with the results obtained by Ref. [34], the percentages of trees with permanent damage due to the harvest reach 10.1%, a value that is higher than the average percentage determined in our work (3.5%); however, when comparing the traditional methods with reduced impact methods, there is a lower percentage of damage in the second method, which also corroborates the importance of RIL methods to ensure the sustainability of forest management. Ref. [10] correlates the logging method with the percentage of damaged trees, the lowest percentage being the one that uses reduced impact methods with 4.1% of total damage, which confirms that the RIL damages residual trees to a lesser extent. Another coincident answer in the evaluation of damages on residual trees is the correlation between the diameter of the thinned tree with the affected trees, and Ref [4] reports percentages similar to those obtained in our work (average total damage 6.7%) and linearity between the basal area extracted and the percentage of damage of residual trees.

5. Conclusions

Finally, we can conclude that there is a correlation between the intensity of thinning and the temporary damage rates of the residual trees. The damage type of the residual trees is correlated with the intensity of thinning, with the DBH of the thinned tree and with the structure of the forest, since the damage rate will depend exclusively on the number of large and small trees that make up the total number of stand trees. The damage rates obtained in our study are within the percentages achieved in other tropical areas using mainly RIL methods, which is undoubtedly an ecological framework that allows planning harvest activities in Ecuador.

Acknowledgements

Conflict of interest

The authors declare no conflict of interest.

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