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ORIGINAL RESEARCH ARTICLE

Performance of different logging systems in the shelterbelt cutting of the *Nothofagus pumilio* forest in America

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ABSTRACT

Nothofagus pumilio forests constitute the most economically important forest stand in southern Argentina and Chile. Total volume stocking and volumetric yield vary according to site quality, degree of occupation, growth stage and forest history of the stand. The objective of this work was to evaluate the stocking and the productive potential in quantity and quality of products for the sawmilling industry, using three harvesting systems (short logs, long logs and complete shafts) in the protection cut of a *N. pumilio* forest of site quality III in Tierra del Fuego (Argentina). The trials were conducted in an irregular mature forest with two strata and abundant regeneration (3.0 ha; RDI 93.8–113.4%). Total volumes varied between 726.5 and 850.3 $m^3 \cdot ha^{-1}$, with a volume/basal area ratio of 11.8 to 12.1 $m^3 \cdot m^{-2}$. The harvesting rates obtained were: 45.5% for complete logs, 21.3% for long logs and 22.4% for short logs. A model was used to estimate the timber volume for each system, where full shafts resulted in a significant increase in timber volume. Considering new alternatives in the planning of harvesting in forest management for *N. pumilio* forests, such as the system of complete shafts, allows obtaining higher harvesting rates, increasing the benefits for the forestry company and minimizing the damage to the forest, due to the shorter distance of the machinery in the forest harvesting.

Keywords: Forest Harvesting; Harvestable Volume; Volumetric Yield; Structure; Lenga; Patagoni

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1. Introduction

The forests of *Nothofagus pumilio* (Poepp. et Endl.) Krasser (lenga) are the most economically important forest stand in terms of area and volume in southern Argentina and Chile[1,2]. *Nothofagus pumilio* is a semi-lyophilic species that presents an average installation of 623,100 seedlings per hectare in high forest cover[3], requiring greater light availability in order to develop[4]. The regeneration method used which is adapted to this species is protective cutting, which consists of the gradual opening of the canopy to allow regeneration to develop. This alternative proposes the transformation of the virgin forest into a regular system that allows increases in growth, health and timber quality, improving harvesting rates and subsequent yields in the sawmill[5,6].

In Tierra del Fuego there are 215,000 ha of productive *N. Pumilio* forests[1]. The total volume stock with bark varies between 300 and 1,300 $m^3 \cdot ha^{-1}$ according to site quality, degree of occupation, growth phase and forest history[6]. The growth phases are stages of the natural development cycle of the Nothofagus spp. forest of variable duration which are associated with age ranges and particular structures[5]. These stages begin with the initial optimal growth, characterized by a smooth bark along the trunk, then the final optimal growth where the bark begins to crack. In the aging phase the bark is cracked and forms plaques. The crumbling phase is characterized by bark detachment and deep cracks along the trunk[5]. For these forests there is a classification of site classes[7] that presents five qualities (I to V) defined for forestry use in Southern Patagonia, with site quality being the main factor affecting stand volumetric yield[6]. Most productive forests in Tierra del Fuego develop in site class III and at maturity possess a dominant height ranging from 20.5 to 24.0 m (IS_{60} = 13.15–16.50 m)[7].

Since the beginning of forestry activities in Tierra del Fuego (Argentina), the traditional harvesting practice has consisted of the cutting of the best individuals (floreo)[8]. As a result, logged forests have remnant individuals that are over-mature and of low quality. However, in stands of better site quality, intensive logging was carried out, including clear-cutting of large areas when firewood was extracted in the vicinity of urban centers[8,9]. Currently, with the application of protective felling, part of the trees is marked as canopy protection and another part is not harvested due to low yields, resulting in an incomplete cut in this regeneration method. In the 1990s, the demand for timber in the local market was based on large squares (planks, boards and suspenders), making it necessary to carry out a high selection of logs (4–6 m long, diameters greater than 35 cm and good health) of type “A” and “B” according to the classification proposed by Cordone and Bava[10]. The traditional harvesting system consists of turning, sanitary basal cutting (cutting at the base of the felled tree to eliminate irregularities in the trunk due to felling and rotting in the first log) and the production of logs of fixed dimensions in the forest. The disadvantages of this system include: (1) the poor working conditions for the chainsaw operator (since when selecting the logs in the felled tree, it is necessary to make several cuts between the residues); (2) a high selection in the quality of the logs (the best quality logs are used); (3) under-utilization of the skidder’s performance (generally the limiting factor is the number of logs and not the volume to be harvested); (4) an increase in the loss of logs (10 to 20% of the volume generated) during logging, because they are difficult to access or because they are found among the residues[8]. As these logs are limited in the forest (5% and 20%, respectively), the traditional harvesting system results in a low cutting percentage and a harvesting rate of 5 to 10% (volume of logs/total forest volume), with timber volumes varying between 40 to 60 $m^3·ha^{-1}$. With the technological improvement in sawmills, lower quality logs (“C”, with localized defects or poor shape) and fine point diameters greater than 20 cm were incorporated into production. This lower quality in the logs determines the need to compare the volumetric yield between the traditional harvesting system with other systems to evaluate the quality and quantity of logs harvested. The objective of this work is to evaluate the stock and the productive potential in quantity and quality of products for the sawmilling and synthesis industry, using three harvesting systems (short logs, long logs and complete logs) in the protection cut of a *N. pumilio* forest of site quality III in *Tierra del Fuego* (Argentina).

2. Methods

Area under study. We worked in a pure forest of *N. pumilio* in the *San Justo ranch, Tierra del Fuego* (54°06’S, 68°37’W), site class III[7], where the Los Castores sawmill carries out forest harvesting according to the regulations of the provincial forest law No.145, using as a reproduction method high forest under protective cover (protection cut)[5].

Forest characterization. For this study, an area of 3 ha was randomly selected in a non-intervention forest (BSI) where 15 contiguous plots of 40 × 50 m were made. In each plot, forest structure was characterized by dominant height (100 tallest trees per hectare), basal area, mean square diameter (MSD), number of trees per hectare, number of stands per hectare (1 to 10 cm DBH), social or canopy class (dominant, co-dominant, intermediate or suppressed) and growth stage of individuals (initial optimum growth, final optimum growth, aging or collapse)[5].

Marking and turning. In the selected area, seed trees were marked according to the protection cutting treatment, leaving 40% of the original basal area standing, with a maximum distance between trees of 9 m. The selected seed trees had to have a wide canopy, be dominant and have a low slenderness coefficient because the trees selected were the least susceptible to wind and snow damage[11,12].

The harvesting was carried out by trained personnel using chainsaws. Two types of felling were evaluated in the 3 ha selected from the forest without intervention (BSI). The first consisted of turning over the best quality individuals according to the criteria of the chainsaw operator (FL) without cutting the seed trees (this type of felling, similar to flowering, is traditionally applied in the region). While in a second stage the protection felling was completed according to the marking carried out (CP). The volume of all the trees that were felled was measured (total volume with and without bark) including the stump, branches and trunk up to 1 cm in diameter. Partial volumes were determined using the Smalian formula[13,14].

Harvesting systems. Three harvesting systems were used in the 3 ha selected in five contiguous plots of 40 × 50 m each. In the first treatment, a system of harvesting was applied, which was consisted of short logs (TC) for sawing, with 3 to 5 m in length and a diameter in fine point greater than 20 cm. The short logs were with no more than one third of rot on the most affected face, without bends in the longitudinal axis (arrow), or generalized defects (logs A, B and C). In the second treatment, logs were extracted without length restriction (TL), with the same characteristics as the previous treatment, but with fewer demands on the arrow and the external characteristics of the logs. In the last treatment, a complete log extraction (F) was carried out, and a cut at the base of the tree and another cut up to a diameter of 20 cm in the shaft. In this treatment, the trunks were cut with a chainsaw in the stockpile field.

Volume characterization. The volume was separated into timber (shafts, short logs and long logs), chipping logs and cull logs. Chippable logs had a length of 2.44 m and a minimum bark diameter of 10 cm, with no more than two-thirds rot on the worst side. All commercially unusable material was considered as waste (without taking into account the sale of firewood). The Smalian formula was used to calculate the volume of logs. In the case of shafts, the Newton formula was used due to their large dimensions[15]. The total and usable volume of the canopy was characterized using the functions proposed by Martínez Pastur[16], which incorporates the site class as a variable.

Estimation of standing volume of harvestable volume. To compare the volumetric yield of the remaining trees in the canopy, an estimation of the volume of standing logs was made using the model[17].

$$VMSC = M \times I \tag{1}$$

Where, "M" = non-linear model that predicts the bark-free timber volume 44(VMSC) of individual trees, and "I" = discrimination index with a value of 0 or 1 (0 = non-timber; 1 = timber) generated based on empirical classifications.

The value of the "I" index is obtained from a table in which the variables social class (CS) (S-suppressed, I-intermediate, C-codominant and D-dominant), tree development stage (COI-initial optimum growth, COF-final optimum growth, ENV-aging, DM-des-moronamiento) according to Schmidt and Urzúa[5], and DBH in cm are used to obtain it. The "M" component represents the volume of bark-free timber that a tree whose I component is equal to 1 will yield. The M model was represented by the following equation adjusted by non-linear regression techniques:

$$M = a \times DAP^{b} \tag{2}$$

Where, a and b = parameters of the equation and DAP = diameter at 1.3 m (cm).

Statistical analysis. An analysis of variance was performed to analyze the effect of the different harvesting treatments (TC, TL and F) on forest structure variables (DCM, basal area, dominant height, density and percentage of individuals for each CS and tree development stage) by means of the F test, using Tukey's test for the comparison of means.

The significance level used for all cases was $\alpha = 0.05$. A comparison of the "M" component of the standing log volume model was made for treatments TC, TL and F. All models were fitted using non-linear regression techniques. The algorithm proposed by Marquardt[18] was used to estimate the parameters. The statistical evaluation of the models was carried out through the adjusted coefficient of determination (r^2) and the average absolute error. To evaluate the behavior of the discriminant "I" of the estimation of the volume of standing logs versus the sample (0 = non-timber; 1 = timber), the frequencies of individuals that could contribute logs and those that could not contribute logs were analyzed by performing a Chi-square test between the observed and calculated frequencies, discriminating by social class and growth stage.

3. Results

Characterization of the initial and remaining structure under different types of logging. The logged forest presented the structure of an irregular mature forest, with two well-differentiated strata and abundant regeneration by coppices (**Table 1**). The forest belongs to site class III (according to the classification proposed by Martínez Pastur[7]), with dominant heights that fluctuate between 22 and 23 m. The average density values varied between 93.8% and 113.4% according to the Reineke density index proposed by Martínez Pastur[16], indicating that the stands were at the maximum degree of occupancy (59.7 to 73.3 m^2 of basal area per hectare). These stands can be classified as forests in the aging phase (40.5% to 67.1% of the trees are in this phase), with a low percentage of individuals in the collapse phase (4.6% to 9.1%), most of which were left as a protective canopy after felling. This type of structure is the most representative of the productive virgin forests of Tierra del Fuego, due to its site quality and its high proportion of timber individuals[7]. When analyzing the original structure among the treatments of different harvesting systems, significant differences were detected in the number of trees in the final optimum growth phase and number of intermediate trees in the full-stem treatment with respect to the other two (**Table 1**). Although there are no significant differences, it is observed that treatment F (full shafts) has a greater number of trees (33–35%), with a greater number of individuals in the final optimum growth phase (19–28%) and fewer codominant individuals (5–16%). These differences should be taken into account when analyzing the volumetric yield per hectare. No significant interactions were found in the analysis of variance, which indicates the independence of the treatments.

Table 1. Analysis of variance of the forest structure under study in the different treatments

Treatment	DCM	AB	HD	Density	Density <10	IOC	COF	ENV	DM	S	I	C	D
SITC	43.2	59.69	22.91	411		11.7	16.6a	67.1	4.6	24.8	19.0a	42.3	13.9
SITL	4.5	63.35	22.25	415		3.6	26.1a	62.1	8.2	19.8	16.4a	53.2	10.6
SIF	41.0	73.29	21.84	555	5	5.4	45.0b	40.5	9.1	18.9	30.6b	36.9	13.6
FLTC	47.7b	13.80a	-	77a	0	0.0a	3.9a	93.5ab	2.6	1.3a	10.4a	72.7b	15.6
FLTL	46.0b	14.47a	-	87a	0	0.0a	5.8a	91.9b	2.3	1.1a	1.2a	87.4b	10.3
FLF	41.0a	36.18b	-	274b		3.7b	54.7b	39.4a	2.2	20.2b	32.2b	46.7a	10.9
CPTC	37.5	35.53	-	321	31b	6.2	27.7a	58.3	7.8	22.8a	24.9a	46.7	5.6
CPTL	38.5	38.75	-	332	20ab	5.4	32.5ab	56.6	5.5	25.0a	21.7a	45.8	7.5
CPF	39.2	42.93	-	385	3a	11.1	41.3b	43.3	4.5	24.4a	27.1b	44.4	8.1
RTC	58.5b	24.17a	-	90a	0	0.0	4.5a	94.4	1.1a	0.0	8.9a	55.5	35.6
RTL	61.4b	24.60a	-	83a	0	0.0	0.0a	83.1	16.9ab	0.0	2.3a	62.7	35.0
RF	46.6a	28.97b	-	170b		0.0	34.2b	47.0	18.8b	18.8	23.5b	35.3	22.4

BSITC = initial situation treatment of short logs; BSITL = initial situation treatment of long logs; BSIF = initial situation treatment of full shafts; FLTC = flowering treatment of short logs; FLTL = flowering treatment of long logs; FLF = flowering treatment of full shafts; CPTC = protection cutting treatment of short logs; CPTL = protection cutting treatment of long logs; CPF = protection cutting treatment of full shafts; RTC = remnant forest, short log treatment; RTL = remnant forest, long log treatment; RF = remnant forest, full log treatment; MWD = mean square diameter (cm); AB = basal area ($m^2 \cdot ha^{-1}$); HD = dominant height (m); Density = number of trees per hectare (n·ha^{-1}); COI = initial optimum growth (%); COF = final optimum growth (%); ENV = aging (%); DM = decay (%); S = suppressed (%); I = intermediate (%); C = codominant (%); D = dominant (%). In each column, different letters indicate significant differences (P < 0.01).

In the analysis of variance of the flowering structure (FL), significant differences were detected in most of the variables studied (**Table 1**). In this harvesting system, 23% of the original basal area in the short log and long log treatments and 50% of the original basal area in the full-stem treatment was removed respectively, and then harvesting trees between 30–70 cm DBH with an average of 41-48 cm. Between 77 and 274 trees were felled, which represented the elimination of 19–50% of the individuals. More than 90% of the trees were in the aging stage (FLTC and FLTL treatments), which are the individuals that provide the highest percentage of sawable healthy wood[19], being mostly co-dominant (good stem shape with wide crowns and no external damage). The treatment of flowering with complete shafts (FLT) showed differences in the growth stage and social class of the felled trees, with a greater number of trees that were turned over and the percentage of optimal final, -intermediate and suppressed growth was significantly higher in FLT than in the FLTC and FLTL treatments.

With the application of the CP treatment, the forest presented a more homogeneous structure, as the differences found in the analysis of variance of the flowering treatment in the variables of DCM, AB, density, growth phase and social class were not observed. When the cutting of 60% of the basal area was completed, 70–80% of the individuals were cut. In this second stage, mainly trees in final optimum growth, crumbling and some in the aging phase not felled during flowering were harvested; most of them being intermediate or dominant.

The protective canopy (40% of the original basal area) consisted of good-sized trees (46.6 to 58.5 cm DCM) in the aging-decay stage (65–100% of the individuals) of co-dominant-dominant social class (57–98% of the individuals).

Estimation of standing timber volume. The observed bark-free timber volume-DAP values show a heterogeneous and dispersed distribution due to the presence of non-timber trees and different harvesting systems. The modeling of the bark-free timber volume is difficult because of the null values (VTSC = 0) along the diameter gradient. In order to be able to discriminate the trees that presented timber volume without bark, the model (1) was adjusted where a discriminant "I" was applied to separate those that provided log volume (I = 1) from those that did not present log volume (I = 0). **Table 2** defines the discriminant key, where the construction of the I component was carried out by analyzing the probabilities of finding individuals that did or did not contribute log volume without bark. The quality of the discriminant was evaluated by performing a Chi-square test between the observed and modeled frequencies, which was adequate since no significant differences were observed (**Table 3**).

Table 2. Component "I" of the model (1) for estimating the standing harvestable volume

Tree growth phase	Social class	DBH (cm)	I
Optimal initial growth	Deleted		0
	Intermediate	<30	0
	Intermediate	≥30	1
	Codominant	<30	0
	Codominant	≥30	1
Optimal final growth	Deleted	<25	0
	Deleted	≥25	1
	Intermediate	<25	0
	Intermediate	≥25	1
	Codominant	<30	0
	Codominant	≥30	1
	Dominant		1
Aging	Deleted		0
	Intermediate	<35	0
	Intermediate	≥35<40	1
	Intermediate	≥40	0
	Codominant	<35	0
	Codominant	≥35<55	1
	Codominant	≥55	0
	Dominant	<65	1
	Dominant	≥65	0
Crumbling	Deleted		0
	Intermediate		0
	Codominant	<35	0
	Codominant	≥35	1
	Dominant		0

The inclusion of DAP as an independent variable explained between 70 and 80% of the variation found in the data, this being an adequate adjustment, considering that the dependent variable often has an erratic behavior that is difficult to explain. The adjusted models for each harvesting system were defined by the parameters and statistics presented in **Table 4**. The models showed a low average absolute error in the prediction of the volume of bark free timber. For the full-stem harvesting system, it was observed that the model differs significantly from that of timber volume without bark-short log and timber volume without bark-long log when comparing the confidence intervals of the parameters, resulting in a higher timber volume when applying this system. **Figure 1** shows that a harvestable tree of 40 cm DAP generates 50% more timber volume than a tree of the same diameter for the short log or long log system.

Table 3. Chi-square analysis for the discriminant "I" of equation (1) of the standing volume estimation model

Tree growth phase	n	Timber volume without bark = 0 Actual (%)	Timber volume without bark = 0 Estimated (%)	Chi-square	Significance *P*
Optimal initial growth	84	95.2	95.2	0.131	<0.05
Optimal final growth	417	59.0	56.1	0.594	<0.05
Aging	748	47.1	48.8	0.386	<0.05
Crumbling	103	86.4	94.2	2.713	<0.05
Social class					
Deleted	276	97.8	98.2	0.000	<0.05
Intermediate	298	61.7	63.1	0.064	<0.05
Codominant	605	39.2	39.5	0.003	<0.05
Dominant	173	43.9	45.1	0.012	<0.05

Table 4. Parameters and statistics of the "M" component of the standing volume estimation model for different harvesting systems

Model	a	IC inf	IC sup	b	IC inf	IC sup	R^2 aj	n	MAE (m^3)
VMSC F	0.000436841	0.0002563	0.0006173	2.03513	1.92699	2.14328	70.72	338	0.2220
VMSC TC	0.00000667144	0.000001484	0.00001186	2.9975	2.82926	3.16573	80.56		0.1810
VMSC TL	0.0000123267	-5.172E-8	0.00002470	2.83064	2.60983	3.05144	68.24		0.2664

a, b: model parameters; CI: 95% confidence interval; inf: lower; sup: upper; R^2 aj: R^2 adjusted for 95% significance; MAE: mean absolute error; F = whole log treatment; TC = short log treatment; TL = long log treatment; VMSC = volume of timber without bark.

Table 5. Evolution of the volume (total, timber, chippable and waste) during protection logging

Treatment	VTCC	VMSC	VASC	VD
BSITC	726.5 (12.1)	99.9a (1.7a)	360.8ab (6.0a)	265.7 (3.5a)
BSITL	750.4 (11.9)	92.9a (1.4a)	409.8a (6.5a)	247.7 (3.9ab)
BSIF	850.3 (11.8)	342.2b (4.8b)	265.2b (3.7b)	242.8 (3.4b)
FLTC	162.5a (11.8a)	47.1a (3.3a)	57.1 (4.3a)	58.3 (4.2a)
FLTL	159.9a (11.0ab)	53.4a (3.5a)	58.1 (4.2a)	48.3 (3.3a)
FLF	387.1b (10.6b)	248.1b (6.8b)	66.3 (1.9b)	72.7 (1.9b)
CPTC	411.3 (11.6)	74.1a (2.1a)	176.6ab (4.8a)	160.6 (4.6)
CPTL	440.5 (11.4)	70.2a (1.8a)	215.4a (5.6a)	154.9 (4.0)
CPF	487.4 (11.3)	255.9b (5.9b)	96.8b (2.3b)	134.7 (3.1)
RTC	315.2 (13.0)	25.9a (1.1a)	184.2 (7.6a)	105.1 (4.3b)
RTL	309.9 (12.6)	22.7a (0.9a)	194.4 (7.9a)	92.8 (3.8a)
RF	362.9 (12.5)	86.4b (3.0b)	168.4 (5.8b)	108.1 (3.7a)

Volume to basal area ratios ($m^3 \cdot m^{-2}$) are shown in parentheses; BSITC = initial situation short log treatment; BSITL = initial situation long log treatment; BSIF = initial situation whole log treatment; FLTC = flowering short log treatment; FLTL = flowering long log treatment; FLF = flowering whole log treatment; CPTC = protection cutting short log treatment; CPF = protection cutting short log treatment; CPTL = protection cutting treatment of long logs; CPF = protection cutting treatment of complete trunks; RTC = remaining forest treatment of short logs; RTL = remaining forest treatment of long logs; RF = remnant forest full-log treatment; VTCC = total volume with bark ($m^3 \cdot ha^{-1}$); VMSC = volume of timber without bark ($m^3 \cdot ha^{-1}$); VASC = volume of chips without bark ($m^3 \cdot ha^{-1}$); VD = volume of waste with bark ($m^3 \cdot ha^{-1}$). In each column, different letters indicate significant differences ($P < 0.01$).

Characterization of volumes for the different types of logging and harvesting systems. In the initial total volumes, no significant differences were found among the treatments tested (726.5 to 850.3

m3·ha-1) (**Table 5**), and the volume/basal area ratio was practically constant (11.8 to 12.1 $m^3 \cdot m^{-2}$). When analyzing the total volume harvested through thinning, the full-stem system differed significantly from the short-log and log-log treatments, with more than double the yield in forest harvesting. The harvesting rates obtained were 45.5% for full shafts, 21.3% for long logs and 22.4% for short logs. In terms of timber volume, the yield of complete shafts represented 64.2% of the total volume harvested, compared to 29% and 33% for short and long logs, respectively. For chip and cull volumes, no significant differences were found between treatments.

An increase in VMSC was observed in the short log (27.0 $m^3 \cdot ha^{-1}$) and long log (16.8 $m^3 \cdot ha^{-1}$) treatments, while the harvesting of complete logs did not vary greatly (7.8 $m^3 \cdot ha^{-1}$). The volumes harvested (VMSC) showed significant differences for the whole-stem treatment (52.5% of the VTCC compared to 18% and 16% for short and long logs, respectively) based on similar harvest volumes. It was observed that there was an increase in the volume of chips in the short log and long log treatments, with no differences in the volume of waste between treatments. The large amount of full-stem timber volume can be deduced as a contribution of wood that is produced from the chip volume. This is because a greater number of low diameter logs were included, as opposed to the other treatments that underutilize the timber volume (**Figure 2**). The number of logs and timber volume produced by harvesting whole logs increased for the 25–30 cm to 40–45 cm diameter classes. In the short log treatment, 115 logs of 0.64 m^3 each of average volume were obtained, while in the whole log treatment, 710 logs of 0.38 m^3 each were harvested.

4. Discussion

The number of logs and the volume of timber produced by harvesting whole trunks increases for the 25–30 cm to 40–45 cm diameter classes. This volume represents very important values of healthy wood that is usually left in the forest or standing, and is despised because of its low individual log volume. It should be noted that chainsaw operators

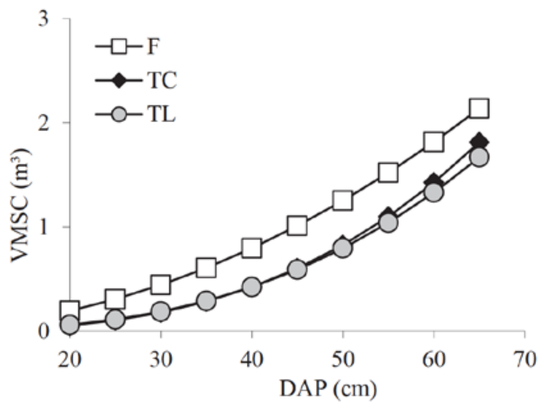

Figure 1. Model for estimating the harvestable volume of timber trees for different harvesting systems; VMSC = volume of timber without bark.
Log under bark volume model obtained for each logging system. VMSC = log under bark volume.

are paid per log (rarely per volume), so contractors demand large logs of good quality.

The studies of volumetric yields of forest harvesting in *N. pumilio* forests belong to the whole range of site classes. The total volumes vary between 378.2 and 945.3 $m^3 \cdot ha^{-1}$ while total volume/basal area ratios between 8.91 and 14.03 $m^3 \cdot m^{-2}$, presenting volumes obtained in a protection cut that vary, according to different authors, between 33.0 and 266.5 $m^3 \cdot ha^{-1}$[9,20-26].

The values obtained by González[23-25], Garib[24] and Daffunchio and Villena[25] are comparable to those obtained in the full-stem plots, having used similar harvesting systems. The harvesting rates obtained varied between 20% and 35%, which implies that the utilization of the felled trees was maximized. These harvesting rates represent between 3.5 and 7.6 $m^3 \cdot m^{-2}$ of timber volume/basal area. The results obtained by Ferrando[21] in a mixed forest of *N. pumilio*-*N. dombeyi* (dominant height of 24 to 25 m) are comparable to the yields of the short log and long log treatments (harvest index of 13.2%). The harvest indexes presented in Table 6 for harvesting by flowering or thinning vary between 1.5% and 11.2%, without considering the full-stem treatment. The full-stem methodology was applied on a large scale in the Los Cerros ranch (Tierra del Fuego, Argentina)[26] giving results comparable to those of this study. Values of 177.4 and 167.0 $m^3 \cdot ha^{-1}$ of bark-free timber volume (**Table 6**) were obtained using the Variable Retention regeneration method[2,26-30]. The authors state that the volumes extracted were high, since no unnecessary clearing was carried out during the shafts production operations.

The full-stem system increases the volumetric yield of the forest compared to the short log and long log methods, producing other advantages such as less impact on the soil due to the reduced amount of travel made by the forestry machinery[26,30,31], being important to reduce damage to the pre-installed regeneration[32-34] not measured in this study. An undesirable effect is the damage to the remaining trees during harvesting[35], which causes the remaining trees to fall due to windthrow after harvesting[8], being necessary to perform these tasks with extreme care to reduce damage to the remaining trees[35]. Likewise, this system, due to its high yields, allows the use of forests in the worst site qualities[6].

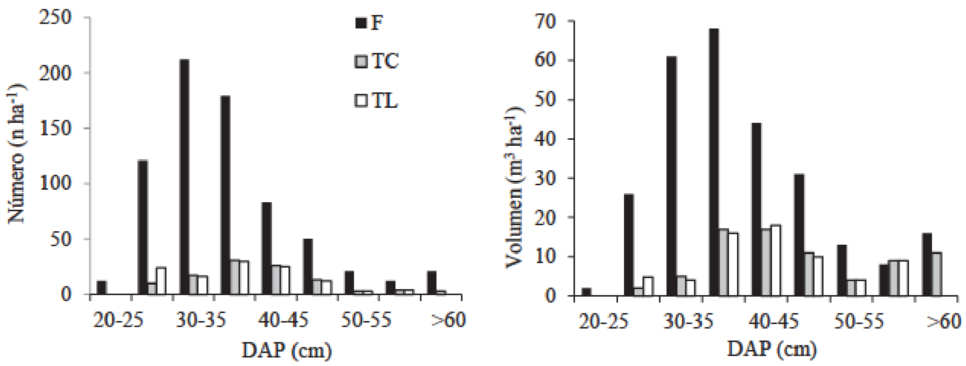

Figure 2. Comparison of the number and volume of logs by diameter class at fine point for the short log (TC), long log (TL) and full log (F) harvesting treatments.

Table 6. Comparison of volumetric yields in different *N. pumilio* forests

Zone	BSI VTCC	BSI VTCC/AB	R VMSC	F VMSC	CP VMSC	VMSC/AB
TC	726.5	12.17	-	47.1 (6.5)	74.1 (10.2)	2.08 (CP)
TL	750.4	11.84	-	53.4 (7.1)	70.2 (9.3)	1.81 (CP)
F	850.3	11.6	-	248.1 (29.2)	255.9 (30.1)	5.96 (CP)
Russfin[a]	945.3	12.53	-	-	190.3 (20.1)	3.83
MonteAlto[b]	776.2	9.28	-	87.3 (11.2)	166.7 (21.5)	3.52 (CP)
Aysén[c]	547.6	11.48	-	60.3 (11.0)	72.5 (13.2)	2.63 (CP)
MonteAlto[d]	633.7	8.91	39.8 (6.3%)	-	-	2.66
MonteAlto[e]	552.7	9.10	44.3 (8.0%)	-	-	4.53
Tolhuin[f]	586.9	10.01	-	-	179.7 (30.6)	5.86
MaCristinaf	535.1	10.53	-	-	152.1 (28.4)	4.14
PretoOestef	750.2	10.41	-	-	266.5 (35.5)	5.69
Cholila[g]	378.2	14.03	-	16.8 (4.4)	-	3.66
Cholila[g]	582.1	9.76	-	8.8 (1.5)	-	0.91
Cholila[g]	756.5	14.03	-	82.4 (10.9)	-	4.85
Tolhuin[h]	659.0	10.73	-	-	33.0 (5.0)	-
Los Cerros[i]	534.9	11.88	-	-	177.4 (33.2)	5.91
Los Cerros[i]	449.5	11.25	-	-	167.0 (37.1)	5.57

In parentheses are the harvest indexes obtained in percentage; BSI VTCC = initial situation total volume with bark ($m^3 \cdot ha^{-1}$); BSI VTCC/AB = initial situation total volume with bark/basal area ratio ($m^3 \cdot m^{-2}$); R VMSC = thinning timber volume without bark ($m^3 \cdot ha^{-1}$); F VMSC = thinning bark-free timber volume ($m^3 \cdot ha^{-1}$); CP VMSC = protection cutting bark-free timber volume ($m^3 \cdot ha^{-1}$); TC = San Justo short log treatment; TL = San Justo long log treatment; F = San Justo whole log treatment; (a) Tierra del Fuego (Chile) in Garib[24]; (b) XII Region (Chile) in González[23]; (c) XI Region (Chile) in Ferrando[21]; (d) advanced optimum growth stand, XII Region (Chile) in Mosqueda[9]; (e) final optimum growth stand, XII Region (Chile) in Mosqueda[5]; (f) Tierra del Fuego (Argentina) in Daffunchio and Villena[25]; (g) Chubut (Argentina) in Chauchard[20]; (h) Tierra del Fuego (Argentina) in Bava and Hlopec[22]; (i) Tierra del Fuego (Argentina) in Martínez Pastur *et al*.[26]

These harvesting systems have implications in the export of nutrients from the forest, being important to leave on the ground all the leaves, fine branches and bark, as these have the highest concentration of nutrients[36-38]. Likewise, the conservation of remnant trees in the regeneration method used, presents benefits in terms of habitat structure for birds[39], mosses[30], understory plants[40] and insects[41], these aspects being very much taken into account in the planning of land use. In this study, the results are presented from a production point of view, being of utmost importance for future research the environmental and social aspects.

5. Conclusions

By thinning the forest, a lower yield in timber volume is achieved compared to protection logging, since there is a high volume of small-diameter logs that remain in the forest with the canopy or standing. On the other hand, there is an additional benefit of transforming the forest into a regular system with all the advantages. The whole-stem method was the one that gave the best results in comparison with the log harvesting method, since it increases the volumetric yield of the forest and has the least impact on the soil. However, special care must be taken to avoid damage to the remaining trees during harvesting, which causes instability of the protection forest. The yields obtained in this study are comparable to studies carried out in Argentina and Chile and can be applied on a large scale without the need to produce wood chips and use forests of low site quality. Considering new alternatives in the planning of harvesting in forest management allows obtaining a higher harvesting rate, increasing the benefits for the forestry company and decreasing the requirements of forest area within the forest area.

Conflict of interest

The authors declare that they have no conflict of interest.

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