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Forty years of silvicultural management in southern *Nothofagus pumilio* primary forests

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Abstract

To achieve sustainability of a forest system it is necessary to apply appropriate silvicultural management, including preservation measures. The characterization of the status and development of the harvested stands, as well as the timber potential of the unmanaged ones, is necessary to achieve a sustainable forest management. In southern Patagonia, *Nothofagus* forests are the basis for the sawmill industry. Since European colonization, different silvicultural management regimes have been applied in primary forests. Forestry policies and available sawmill technologies have also been involved. There is little knowledge about the consequences of the different silvicultural systems implemented, as well as about the regeneration status of the harvested stands and future possibilities of the managed forests. The objective of this work is to analyse the logged, affected from harvesting and current forest structures, as well as the regeneration development during the last 40 years and the consequences derived to forests of southern Patagonia.

The harvesting was applied irregularly between the studied decades (30 ± 15% of the original basal area was removed) creating an irregular forest structure. Large quantities of sawn logs were abandoned in the forest floor and a high percentage of the remaining forest structure was damaged during the harvesting. Negligent management and wind throw produced a huge amount of wasted timber, resulting in a scarce standing log volume of very low quality. Nevertheless, regeneration was successfully installed (222 ± 185 thousands/ha) within the harvested stands. No differences in the harvesting intensity were found with the different theoretical silvicultural methods applied through the years (selective cuts, clear-cuts or shelterwood cuts). As a result, the forests present a low current and future economical potential. Hence, the status of the secondary forest must be improved and regulated in order to achieve sustainability. Otherwise, the local forest industry will suffer from negative consequences, and this valuable resource will not be profitable in the future.

Keywords: Sustainable forest management; Silviculture; *Nothofagus pumilio*; Forest policies; Tierra del Fuego

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1. Introduction

The preservation of native forests should be one of the most important goals in forest management to preserve their biodiversity and the multiple goods and services which they provide (Kozlowski, 2002). Sustainable management is proposed all around the world as a solution to most ecological and socio-economical problems associated with forests. Nevertheless, the demands upon forest resources grow with the increasing world population, especially in the less populated and forested areas (Lindenmayer, 1999). This pressure produces a mismanagement of forests in many regions, as a result of inappropriate social and political decisions. In many developed countries money is invested in enhancing their ecosystems, despite decreasing the immediate economical profitability of the forest harvesting. On the contrary, in developing countries, where most of the last primary forests still remain, the policies usually focus first on the economic demands, neglecting the forest ecosystem preservation.

The timber industry in Argentina is based in the monoculture of introduced, fast growing species, such as *Eucalyptus* L'Hér. or *Pinus* L., usually transforming or misusing the native forest. The native forest has been removed since European colonization via fires, selective logging, transformation to agriculture and cattle grazing, as the economic interests usually have prevailed over conservation goals. Intensive harvesting over the native forest started in the middle of the XX Century in southern Patagonia with the increase of human population. In Argentine Tierra del Fuego 700–1000 ha are logged each year (data from 1980 to 2003), corresponding to a log volume of 40–45 thousand m^3/year. Since the 1960s, with the introduction of fossil fuels as the main energy source, the main consumer has been the sawmill industry, substituting firewood as the principle destination. Other alternative wood uses, such as pulpwood export, are forbidden by the regulation of provincial law number 202.

Nothofagus pumilio (Poepp. et Endl.) Krasser forests constitute the most important forest resource in southern Argentina and Chile (Martínez Pastur et al., 2000; Cuevas, 2002). This native species is a medium shade intolerant, growing in pure or mixed stands. Natural regeneration is successfully carried out in unmanaged Tierra del Fuego (Argentina) forests (Pulido et al., 2000; Rodríguez Flores, 2002), mostly in gap dynamics, which creates an uneven age structure in an irregular, patchy distribution. The management proposals for these forests have changed over time. Clear-cutting (in prescribed 40–50 m wide strips; for more details see Martínez Pastur et al., 2001) and selective cutting were initially applied, having been recently replaced by more complex silvicultural proposals, such as shelterwood or cluster retention patterns (Schmidt and Urzúa, 1982; Franklin et al., 1997; Martínez Pastur et al., 2000, 2001). However, these theoretical methods are not fully applied. So far, only the first cuts have been implemented, with a lack of the final shelterwood removal and any intermediate treatments.

In Tierra del Fuego the performance of a forest management plan prior to harvesting is compulsory. They have a time validity of 5 years and include a study of the target stands and the timber yields to be harvested. Still the percentage of total harvested forests is not very high, 21% of timberland (Collado, 2001), due to the fact that harvestings have been focused in the most accessible and highest site quality State forests. As a result, State forests show a lack of potentially harvestable locations, which produce a critical dilemma for the local sawmills, due to the fact that no overall planning for the whole forest neither exists nor is intended to be developed.

There is little information about the response of *Nothofagus* Blume forests to the management practices implemented over time. Studies focused on secondary *N. pumilio* forests are scarce (Martínez Pastur et al., 2001; Peri et al., 2002), and none of them analyse their evolution after the different management systems are applied, despite the great importance of this task for any future management plan. In this study, human impact derived from harvesting during the last four decades and the forest response to these interventions is evaluated. The hypothesis tested was that forest policies, social changes, and technology enhancement should influence and improve the response and status of the harvested forests. Due to the lack of existing data, a model of the pre and post harvesting forest structures had to be developed. The changes of the harvested forests during the last four decades were analysed and compared in terms of their original, logged, affected from harvesting and current stand structures.

2. Methods

2.1. Study area

Sampling was carried out in the Island of Tierra del Fuego, located in the southernmost province of Argentina (Fig. 1). The maximum altitude is up to 1500 m.a.s.l., while the tree line reaches 600–700 m. The climate is cold oceanic with strong winds, mainly from the southwest. The mean annual temperature is 5.5 °C (1.6 °C in the coldest and 9.6 °C in the warmest months) and frost may occur at any time of the year. Precipitation is evenly spread over the year, with an annual average of 500 mm/year in the south coast of the island and about 1000 mm/year at the tree line (Tuhkanen, 1992; Brancaleoni et al., 2003), declining towards the north. The landscape occupied by forests is mostly that of glacial origin with loess and alluvial materials in the foothills. Acid brown soils are the most common (Frederiksen, 1988). The forests are located south of 54° latitude (Fig. 1) and correspond to the sub-Antarctic forest type (37°–60° south latitude). *Nothofagus* species are the dominant trees: *N. pumilio, N. antarctica* (Forster f.) Oersted and *N. betuloides* (Mirb.) Oersted, sparsely mixed with *Drymis winteri* Forster & Forster f., *Maytenus magellanica* (Lam.) Hooker f. and *Embothrium coccineum* Forster & Forster f. (Moore, 1983). Biodiversity is low compared to other temperate forests, due to the geography, climate and the recent glacial retreat (Deferrari et al., 2001; Spagarino et al., 2001; Martínez Pastur et al., 2002a). Tierra del Fuego forests cover 712 thousand hectares, around 30% of them considered timberland (Collado, 2001). *N. pumilio* is currently the only species of economical interest. It is harvested mainly in pure but also in mixed stands. The dominant heights range from 30 m in the best conditions to 15 m in the poorest timber sites, with an average of 20–24 m (Martínez Pastur et al., 1997, 2002b).

2.2. Sampling methodology

Twenty-five management units (MU) were selected from forest management plans implemented in the last four decades (Table 1 and Fig. 1). A management unit consists of a group of timber stands and constitutes the minimum division in a forest management plan. These units exhibit large variability (between 11 and 192 ha),

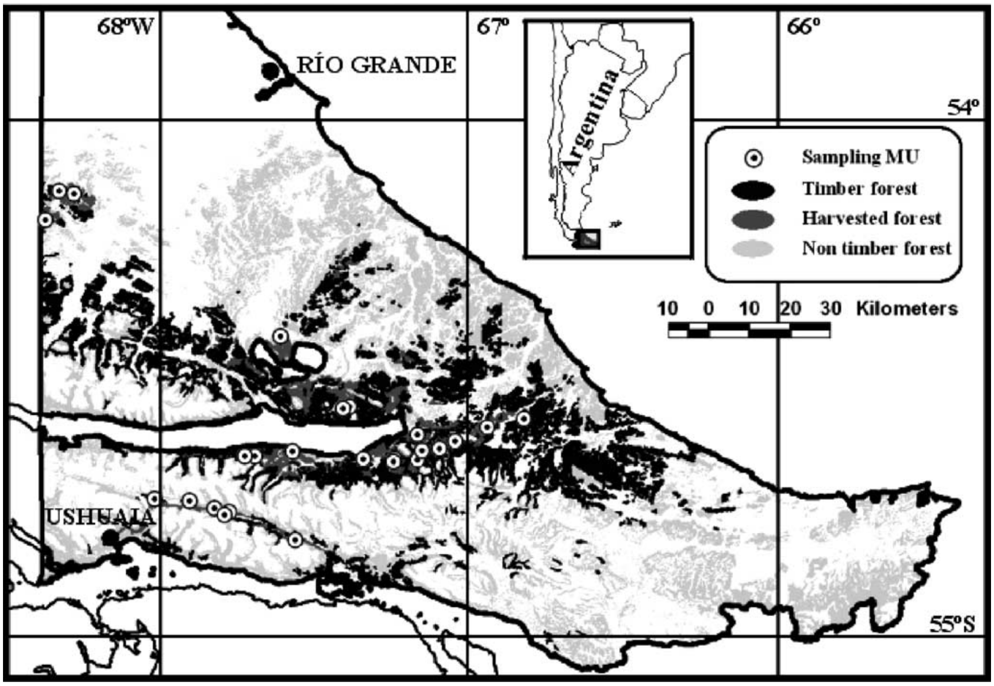

Fig. 1. Location of the sampled management units (MU) in Tierra del Fuego (Argentina), according to forest type determined by Collado (2001).

Table 1
Location, harvesting year and area of the sampled management units (MU)

Management unit	Harvesting year	MU centre latitude (S)	MU centre Longitude (W)	MU area (ha)
Cañadón del Chancho	1961	54°42′44″	68°09′52″	137.9
Las Cotorras	1961	54°42′58″	68°01′58″	31.9
Tierra Mayor II	1961	54°44′17″	67°52′56″	11.0
Tierra Mayor III	1963	54°44′41″	67°54′03″	27.6
Ea. San Justo I	1965	54°02′33″	67°48′17″	193.0
Vega Café	1966	54°43′48″	67°56′18″	39.9
Laguna Escondida I	1969	54°36′57″	67° 47′16″	71.2
Rio Milnak	1971	54°36′13″	67°38′38″	68.0
Aguas Blancas II	1972	54°36′55″	67°15′28″	17.8
Aguas Blancas III	1972	54°37′14″	67°15′36″	20.4
Lote 73	1974	54°21′23″	67°41′54″	92.4
Ea. Rosita	1977	54° 03′ 10″	68° 28′ 48″	85.1
Rio Valdez	1977	54°37′04″	67°22′38″	121.4
Lote 80	1978	54°30′16″	67°26′05″	95.1
Campo Chico	1980	54°32′30″	66°54′32″	156.8
Lote 80 I	1983	54°30′30″	67°27′29″	80.8
Rio Turbio	1983	54°33′44″	67°10′20″	82.6
Tierra Mayor IV	1985	54°47′45″	67°37′38″	88.5
Aguas Blancas I	1986	54°36′56″	67°10′ 19″	33.1
Laguna Escondida II	1987	54° 36′ 58″	67° 49′ 35″	41.3
Ea. San Justo II	1992	54°06′33″	68°35′20″	153.5
Cerro Observación	1995	54°35′23″	67°05′15″	74.8
San Pablo	1998	54°34′28″	67°01′43″	89.4
Lote 93	1998	54°31′11″	66°46′15″	98.7
Aserradero Guaraní	1999	54°35′44″	67°09′13″	189.9

as no fixed patterns exists in their design. They were selected according to several criteria: (1) maximum unit homogeneity, (2) availability of reliable data of the harvesting year, (3) representative and homogeneous distribution over the area and through time, and (4) accessibility. The selection of the 25 MUs was performed with the aid of scanned available forest management maps, aerial photos (1970–1989 flights, 1:20,000–1:80,000) and satellite images (SPOT 1995, LANDSAT 1997 and ASTER 2002) incorporated into a GIS. Additionally, the selected MUs were mapped, and their geographical centres, areas and size were determined (Table 1), excluding a 50 m buffer to avoid the border effect. One cluster of four 50 m × 20 m plots was used to characterise each MU. Once the centre was located with a GPS, the four plots were placed using a random polar coordinates system. This system utilized a double entrance table starting from the centre of each MU: the azimuth (0°–359°) and the percentage (0–100%) of the minimum radius distance. Data were gathered from November to February (spring and summer) of 2002–2003.

The forest structure was analysed according to three strata: trees (diameter at 1.3 m, DBH > 10 cm), saplings (DBH < 10 cm; total height, H > 1.3 m) and seedlings (H < 1.3 m). Within each plot, the DBH from all living or dead trees, windfall after the harvesting and stump diameters (at H = 0.3 m) were measured. In addition, growth phase (initial-under 50 years, optimum-50 to 120 years, maturing-120–250 years, and senescence-over 250 years), crown class (dominant, co-dominant, intermediate and suppressed), and timber quality (stem shape and healthiness) were estimated for each tree (for further information see Schmidt and Urzúa, 1982). To test the harvest efficiency, the marketable logs (with both sides cut, healthy and central diameter >30 cm) lying abandoned on the forest floor were quantified, measuring their diameter and length. Three dominant trees heights were measured to define the site class (SI) following Martínez Pastur et al. (1997). Three DBH increment cores were collected to estimate growth of the parent trees. Cores were air dried, placed in wooden mounts and sanded. Then 5 years growth increments were measured with a digital calliper (+0.01 mm) under magnification. All DBH saplings were measured in three 5 m × 2 m subplots at 0, 25 and 50 m of the central portion of each plot. In each subplot, one dominant sapling was felled, its height measured in the field and its age and DBH growth estimated from slices in the laboratory. Seedlings were characterized in three 1 m × 1 m subplots at the same location as the previous ones. Total and browsed numbers of seedlings, along with maximum and minimum ages estimated from annual growth scars in the field or in the laboratory were measured. Rings were not cross dated to increase reliability in any case, hence ages can only be interpreted as reasonable estimates as Cuevas (2002) reports. Finally, the crown cover was estimated at the centre of each subplot using a spherical densiometer (Lemmon, 1956).

2.3. Modelling of forest tree history and evolution

The MU tree densities, DBH distributions and growths, basal areas and volumes (total over bark volume, TV and tree log under bark LV) were analysed over time. The original forest structure previous to the harvesting, felled structure, affected structure after the harvesting (wind-blown trees and snags) and, current forest structure were modelled as explained in Fig. 2. For the current and original structures, volume models from DBH and H were used (Martínez Pastur et al., 1997, 2002b; Gea Izquierdo et al., 2003). Whereas, when total height could not be measured, models from SI and DBH were selected (Martínez Pastur et al., 2002b). The felled and current LV were calculated with a volume table adapted from Martínez Pastur et al. (2002b). Original structure values were obtained from the sum of the living (estimated their past features from growth cores), felled and affected forest structures. Residual log volumes were estimated using the Huber formula (Huber, 1828).

2.4. Analysis criteria: policies, silviculture and technology

The management units were divided into four groups corresponding to the last four decades. Older stands from previous decades were not included in the study as the stumps and residuals were too deteriorated for a good estimation. The consequences over forest management by the progressive increase in technology and changes of policies through the time were analysed. In the 1960s, the post harvest control and planning was made by the *"Administración Nacional de Bosques"* (ANB), an office linked to the central government in Buenos Aires. Technology was still at a minimum: axes and hand saws were used to fell and log, and oxen were used for dragging. Wood was employed in heating (firewood) and sawmills, that still obtained the energy from boilers. Selective cutting was the predominant silvicultural method, although some areas were clear-cut. The 1970s were characterised by an increase in harvest control as a result of the transfer of forest planning to the *"Instituto Forestal Nacional"*(IFONA), still linked to Buenos Aires. The chainsaw was introduced and tractors were already used for dragging. Although selective cuttings were the most common, the most extensive clear-cuttings existing on the island were implemented during this decade. In the 1980s, the forest activities were still controlled by the IFONA, but an evident enhancement in technology was achieved with the introduction of the first skidder in 1980. Apart from selective cuttings, the first shelterwood cuts were carried out. Until this decade, the trees to be felled were the ones branded and felling was only executed during winter. These last two statements changed with the arrival of the 1990s. Now, the retained overstory was branded before harvesting, being possible to find logging activities year round. In addition, the management and planning control was transferred to the provincial level *"Dirección de Bosques de Tierra del Fuego"*. With this transfer, the forest management plans started to be performed by private sawmills. Hence, the pressure over sawmills decreased as the province institution carried out lighter post-harvest control. Nowadays, the management situation is similar to that in the 1990s. The shelterwood cuts are the prescribed silvicultural method and the technology is higher compared to previous decades, although low in comparison with countries with a longer forestry tradition.

2.5. Statistical analyses

One-way *ANOVA* or non-parametric Kruskal–Wallis (K–W) tests, whether normal and homocedastic variables or not, were used to search for differences in

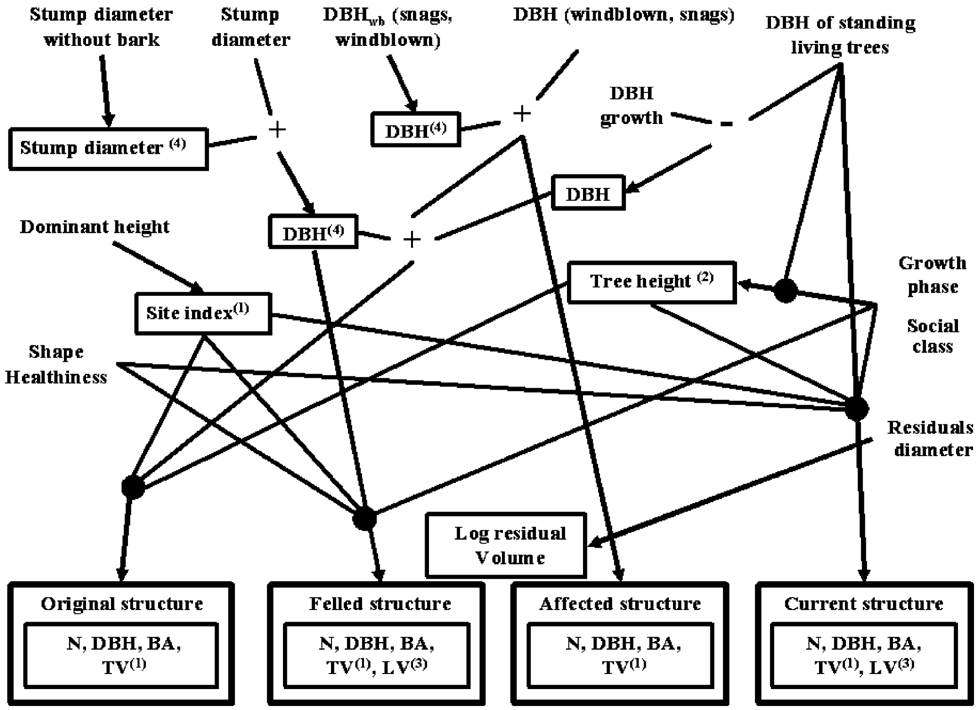

Fig. 2. Outline of the biometric simulation model based on (1) Martínez Pastur et al. (2002b), (2) Martínez Pastur et al. (1997a), (3) Martínez Pastur et al. (1997b) and (4) Gea-Izquierdo et al. (2003). DBH, diameter at breast height (cm); DBH_{wb}, DBH without bark (cm); TV, total over bark volume (m^3); LV, tree log under bark volume (m^3); N, tree density (trees/ha).

the same forest structure between decades. Significant differences between pairs of means in *ANOVA* were analysed by Tukey's test, while differences between medians of two groups in K–W were carried out by the Mann–Whitney (M–W) non-parametric test. Statistical significance of differences between forest structures were conducted by two-tailed Student's t tests. The non parametric significance Wilcoxon test for paired samples was used to check for differences between previous and post harvesting average growth. Significant differences were considered in all analyses for $\alpha = 0.05$.

Table 2
Original (OS) and felled (FS) forest structure: density (N), diameter at breast height (DBH), percentage of the original basal area (PBA), total over bark volume (TV) and tree log under bark volume (LV)

Decade	OS				FS				
	N (trees/ha)	DBH (cm)	BA (m^2/ha)	TV (m^3/ha)	N (%)	DBH (cm)	PBA (%)	TV (m^3/ha)	LV (m^3/ha)
1960	627.1	31.7	60.5	625.7	18.6	38.5	23.7	151.8	72.3
1970	566.1	36.0	63.0	686.8	31.4	42.2	34.1	246.9	115.8
1980	568.2	34.7	61.6	661.1	23.3	43.9	29.5	204.6	92.3
1990	462.4	36.3	52.6	589.3	28.0	40.8	32.2	205.1	103.4
F	1.25	0.90	1.21	0.56	0.80	1.04	0.54	0.82	0.72
P	0.318	0.455	0.297	0.650	0.507	0.397	0.660	0.498	0.554

F, Fisher test; P = probability level. Different letters mean differences by Tukey test at $\alpha = 0.05$.

3. Results

3.1. Forest structure evolution throughout the period

The site quality index (SI) distribution of the studied stands (Martínez Pastur et al., 1997) was according to the average values of Tierra del Fuego reported by Martínez Pastur et al. (2000, 2002b): 2% belonging to site quality I–II (tree mature heights up to 24.1 m), 29% to III (20.6–24.0 m), 55% to IV (17.1–20.5 m), and 14% to V (<17.0 m). The mean stand dominant height (±standard deviation, S.D.) was 20.2 ± 1.6 m.

Over time, the original forest tree density, DBH, basal area (BA) and TV were homogeneous (Table 2). The BA ranged from 53 to 63 m^2/ha, while TV from 590 to 690 m^3/ha. The natural forest stand structure variability was reflected in the S.D. between MUs (BA S.D. = 9.3 m^2/ha, TV S.D. = 137.9 m^3/ha). Contrary to our hypothesis, there was no significant difference in the harvesting intensity (felled structure) among the four decades. The percentage of felled BA ranged from 24% in the 60s to a maximum of 34% in the 70s (Table 2). The mean felled DBH (41 cm) did not change over time and was significantly higher than the original forest structure DBH, which averaged 34 cm (t = 4.12, $P < 0.001$). Thus a selection among the largest trees has been done in the whole period. Therefore, the retained overstory averaged lower DBH than the original forest structure (t = 4.99, $P < 0.001$). Harvested log without bark volumes did not either differ over the time, with mean values ranging from 72 to 116 m^3/ha, in the 1960s and 1970s decades, respectively (Table 2). The log residuals (LV) averaged 7.4 m^3/ha during the whole period, with no significant differences between decades (F = 2.54, P = 0.084).

The affected structure in BA did not present significant differences between groups (F = 0.81, P = 0.505), ranging from 17 m^2/ha in the 1960s, to 22 m^2/ha in the 1970s and 1990s. Besides, the affected structure in BA equalled that of the felled one (t = 1.134, P = 0.131). The irregularity of the harvested stands was highlighted again by the statistics: %BA S.D. = 13.4% and TV S.D. = 71.8 m^3/ha. The DBH of the affected trees neither changed over the time nor showed different patterns from the original stands (t = 0.733, P = 0.467) (Table 3).

The current forest structure presents significant differences among decades in tree density, percentage of the original basal area, total over bark volume and log under bark volume (Table 3). Except in the MU "*Vega Café*", which was harvested in 1966 (Fig. 3), no stand has recovered its original basal area ($t = -8.295$, $P < 0.001$ for whole data set and $t = 2.61$, $P = 0.022$ for the 60s). The current BA values varied from 14.9 to 46.3 m^2/ha. LV ranges from 39.3 to 106.2 m^3/ha, with the same trend increasing towards the oldest harvested stands of BA and TV (Table 3). The mean annual DBH growth disclosed significant differences in the last 15 years. The MU harvested in the 1970s (2.9 mm/year) and 1980s (3.0 mm/year) averaged greater DBH growth than the other two decades, although the Tukey test did not detect any significant differences between pairs (Table 3). The mean annual DBH growth during the 5 years after the harvesting (mm/year) was higher than the mean diameter annual growth (MDAG) of the 20 years previous to the harvesting (Z = 4.51%, $P < 0.001$; post-harvesting MDAG > pre-harvesting MDAG = 64.95%; n = 234, average ± S.D.: 2.62 ± 1.40 and 2.12 ± 0.97 mm/year, respectively). The relative diameter growth increment 5, 10, 15 and 20 years after the harvesting in comparison with previous 20 years growth was 132, 139, 145 and 142%, respectively.

3.2. Forest regeneration

The mean age of the analysed dominant saplings was 19 years old, while the oldest reached 102 years old. Along the 300 sampled points, in only one MU (harvested in the 1970s) no tree regeneration (including both seedlings and saplings) was found. Some dominant saplings were established prior to the harvesting, so it was decided to compare them separated from the saplings established after the harvesting or the 10 years before (hereafter *"young"* and *"old"* saplings). This analysis was conducted in order to check for possible differences in behaviour and to characterise the regeneration related directly to the canopy opening. Fifty-three percent of the points included saplings (159 sampled saplings), wherein 77% were younger than the harvesting age plus 10. These *"young"* saplings averaged greater diameter growth than the *"old"* ones (average ± S.D.: 2.28 ± 2.2 and 1.58 ± 0.68 mm/year, respectively),

Table 3
Affected (AS) and current (CS) forest structure: density (*N*), diameter at breast height (DBH), percentage of the original basal area (PBA), total over bark volume (TV), tree log under bark volume (LV) and diameter annual growth of last 15 years (MDAG)

Decade	AS				CS					
	N (%)	DBH (cm)	PBA (%)	TV (m^3/ha)	*N* (trees/ha)	DBH (cm)	MDAG (mm/year)	PBA (%)	TV (m^3/ha)	LV (m^3/ha)
1960	27	33.1	27.4	183.0	494.3 a	32.7	2.2 a	46.3 a	439.3 a	106.2 a
1970	33	38.2	36.3	251.7	295.3 ab	32.7	2.9 a	23.9 bc	217.2 b	65.1 ab
1980	29	38.2	34.3	231.5	442.3 a	28.1	3.0 a	31.3 ab	282.3 ab	62.3 ab
1990	48	33.4	43.6	243.7	121.0 b	38.3	2.0 a	14.9 c	146.4 b	39.3 b
F	2.95	1.29	1.56	1.10	7.91	1.03	4.20	10.92	8.28	3.56
P	0.059	0.305	0.228	0.372	0.001	0.397	0.019	<0.001	0.001	0.032

F, Fisher test; *P*, probability level. Different letters mean differences by Tukey test at $\alpha = 0.05$.

although no significant differences were found (M–W = 1807.5; $P = 0.061$). Saplings density was significantly less in the 1990s, with a maximum value of 12 thousand plants/ha for the 1980s, decreasing towards those performed in the 1960's (Table 3 and Fig. 4). There was a significantly increasing gradient in the saplings dominant height through the years ($F = 9.09$, $P = 0.003$). A significant increment in saplings BA was also detected, with the maximum value corresponding to 1970s (7.2 m^2/ha). The mean annual diameter growth (MADG) did not significantly change over the time, exhibiting a maximum of 3.4 mm/year in the 1970s (Table 4). High S.D. in the saplings once again reflected their irregular distribution. This S.D. would increase 1.8 times in density and 3.5 in DBH whether it was calculated within subplots instead than within clusters (MU).

Seedlings densities varied from 442 thousand plants/ha in the 1990s to 54 thousand plants/ha in the 1970s (Table 5, Fig. 4), with a maximum of 1.1 million plants/ha in "*San Justo* I" MU. One-year-old seedlings were present on almost every sampling point (subplot), while the oldest was 46 years old. The number of browsed plants significantly increased over the time, from 3.8% in the 60s to 32.1% in the 90s. As in the previous two strata, great variability within MU was found in all seedlings variables (Table 5), increasing the S.D. if it was calculated within subplots instead of within MU (i.e., 2.16 times in total seedling density).

4. Discussion

Contrary to the hypothesis, the changes in policies and technologies in Tierra del Fuego (Argentina) have not significantly changed the forest management results during the last four decades. Logging intensity,

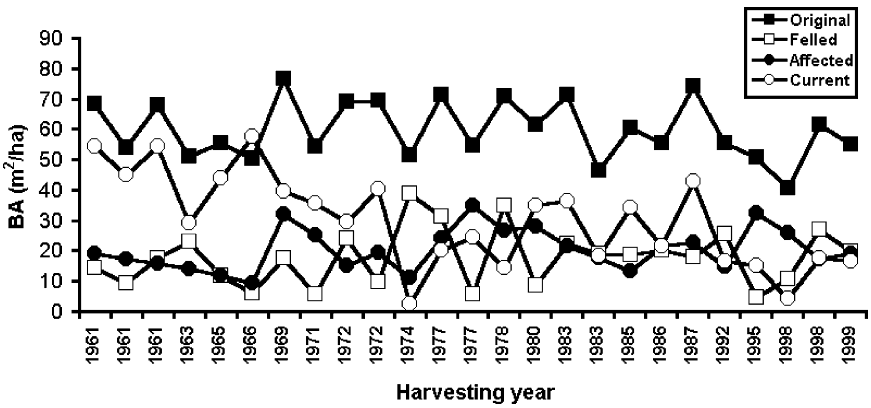

Fig. 3. Basal area of the studied management units in the original, felled, affected and current structures of the canopy trees.

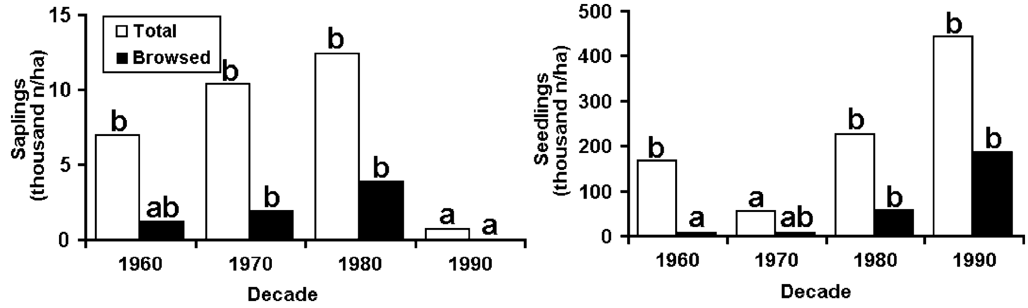

Fig. 4. Total and browsed seedlings and saplings stand density of the studied management units. Different letters show significant differences between medians of each group by Mann–Whitney test at $\alpha = 0.05$.

in quantity and quality has not varied significantly. This absence of differences could be related to the high log quality required by the sawmill industry (healthy and over 35 cm diameter logs), which reduces the potential harvestable volume of the stands independently of the applied silvicultural method. The history of forest management was different in southern Chile. Harvesting yield did significantly change when the shelterwood logging method substituted the selective cuttings in 1992. Wood extractions for pulp, allowed in Chile, are included in these results (Schmidt, 1999).

The harvesting yields are significantly smaller than the potential ones (Martínez Pastur et al., 2000), but the damage over the remaining forest structure depicts the real situation of the timber stands. The felled BA together with the affected stand BA doubles that which is planned to be removed. Wind throw is the main problem for the remaining structure (Rebertus et al., 1997), a problem shared with the southern Chilean forests (Rodríguez Flores, 2002). A possible explanation of the individual wind throw resides in the unfavourable relation DBH-height of the affected trees, as they grew in high density forest. Nevertheless, in our results windblown trees diameter distribution was not biased to any diameter class, as the comparison with the original structure revealed. Other factors might explain wind throw of individual and whole stands (Ruel, 1995; Rebertus et al., 1997). Some of them could be directly related to wind storms and landscape features and others indirectly from the falling of neighbouring trees. Another explanation could be found in the inappropriate and aggressive use of forest machinery during the harvesting. In this way, in the 1990s the damage (mainly wounds on the stem bases) over the retained trees increases. Whereas, the main reason for these large quantities of wood being wind blown is the lack of a complete silvicultural plan, especially the thinning prescriptions. The average felled DBH did not change in time, and was significantly larger than the original one. Therefore, there is an overall impoverishment of the residual

Table 4
Saplings structure: total mean density (*N*), total mean diameter at breast height (DBH), total mean basal area (BA), mean dominant height (*H*), mean diameter annual growth (MDAG) and mean age (*A*)

Decade	*N* (plants/ha)	DBH (cm)	BA (m^2/ha)	H^b (m)	MDAG[b] (mm/year)	A^b (years)
1960	6988 ab	2.8	6.9 ab	5.1a	1.7	35 a
1970	10399 a	2.7	7.2 a	5.0 a	3.4	26 b
1980	12375 a	1.9	3.6 ba	2.9 b	2.4	18 c
1990	700 b	1.9	0.4 b	1.5[a]	1.0[a]	17[a]
F	9.434(+)	1.91	6.43	9.09	1.15	21.90
P	0.024(+)	0.169	0.036	0.003	0.362	<0.001

F, Fisher test; *P*, probability level. Different letters mean differences by Tukey and Mann–Whitney(+) tests, both at $\alpha = 0.05$.
[a] Represent a singleton and was not included in the analysis.
[b] Data of young saplings.d

Table 5
Seedlings characterization: density (*N*), percentage of browsed seedlings (B), maximum age (MA), dominant height (*H*) and average height growth (AHG)

Decade	*N* (thousands/ha)	*B* (%)	MA (years)	*H* (m)	AHG (cm)
1960	165.8 a	3.8 a	10.7	0.21a	3.1a
1970	53.9 b	13.2 ab	9.8	0.40 ab	4.1 a
1980	225.1a	27.2 b	11.5	0.52 b	6.2 ab
1990	442.5 a	32.0 b	6.6	0.42 ab	8.1 b
F	$10.25^{(+)}$	$9.75^{(+)}$	1.20	4.11	5.55
P	$0.017^{(+)}$	$0.021^{(+)}$	0.335	0.020	0.007

F, Fisher test; *P*, probability level. Different letters mean differences by Tukey and Mann–Whitney$^{(+)}$ tests, both at $\alpha = 0.05$.

stands. Besides, the high residual volume left after the harvesting is considerable, which reflects a large amount of saw timber abandoned in the forest floor. In other latitudes and socio-economic circumstances this wood would be destined to lower grade material markets. Nevertheless, these markets do not seem to be profitable in Tierra del Fuego nowadays.

The results obtained from the proposed model for the original structure agree with the expected values for these primary forests (Martínez Pastur et al., 2000, 2002b; Rodríguez Flores, 2002). Forests harvested in different decades displayed differences in their current structure, mainly as the latest harvested MU had shorter periods to recover. The remaining trees reacted to the harvesting in terms of DBH growth (65% of the samples), but no clear common features were found neither among the comparisons according to crown classes nor to site qualities. Similar growths are reported by Rodríguez (2002) for shelterwood cuts in two different stands in southern Chile, with average growths prior to harvesting of 1.7 and 2.8 mm/year. In our results, the growth enhancement shows a decrease after 15 years of the harvesting date. Despite this fact, growth is neither optimised nor easily predictable, as there is great variability between trees depending on each individual history (age, crown class and release from surrounding competitors) and the received damage during the harvesting.

Sapling densities depend on the remaining forest structure, which masks the results interpretation. Despite this fact, it is possible to detect higher densities in the 1970s and 1980s, decreasing towards the 1960s with the increasing dominant height of the saplings (intra-specific competition). Most of the saplings sampled in the 1990s MU corresponded to the suppressed class already established before the harvesting. Szwagrzyk et al. (2001) suggest the importance of seedling banks under the canopy and their capacity to respond with vigorous growth to the canopy openings. It is possible to find seedling banks in *N. pumilio* forests (Cuevas, 2002), which are the origin of the *"old"* saplings previously described (seedlings under 20 years, being the oldest 46 years old). These *"old"* saplings grew less than the *"young"* ones, which reflects a higher vigour in the young ones coinciding probably to the lower age of the released seedlings. Sapling growth was not different between decades, depending probably more on the sapling individual circumstances such as the crown canopy cover or the BA of the stand and interspecific competition. The potential growth of the early stages is not optimised with the implemented forest management, due to the reasons already reported (absence of intermediate practices). This previous statement is confirmed by other authors' results within the whole distribution area of the species. Martínez Pastur et al., (2001) reported an enhancement in diameter increments from 2.3–4.5 mm/year to 4.5–10.0 mm/year in 27-year old thinned stands. In older stands, in continental Patagonia, Peri et al. (2002) measured 4.0 mm/year for a thinning of 489 stems/ha on a 67 years-old stand, compared to 2.0 mm/year in the control stand. Meanwhile, in southern Chile also in pure thinned *N. pumilio* stands, Schmidt et al. (1995) report a DBH growth of 5.2 mm/year in 35–40-year old thinned stands from 2.9 mm/year of the untreated. The regeneration is abundant and seems sufficient to naturally restore the harvested stands. This large amount of regeneration is a frequent characteristic of these ecosystems in southern Patagonia both in Argentina (Martínez Pastur et al., 1999; Pulido et al., 2000) and Chile (Rodríguez Flores, 2002). These seedlings easily responded to the crown canopy opening. The apical growth of the seedlings is higher in open canopies compared to the closed stands, responding to the light availability as in other similar forests of northern latitudes (Agestam et al., 2003). Nevertheless, these seedlings are extremely vulnerable to browsing, which could interfere in the normal restoration of the stands. Browsing increased along the studied period as a consequence of the higher densities of unmanaged wild and domestic macroherbivores, especially in the ecotone areas in the northern distribution area of the forest. The animals usually enter in the harvested forests, especially *Lama guanicoe* Müller, which is displaced from the open areas by the grazing livestock (Martínez Pastur et al., 1999). MUs located in the ecotone as *"Ea San Justo I*", "*Ea San Justo II"* and *"Ea Rosita"* presented the highest percentage of browsed seedlings, with saplings being almost absent. These numbers are again similar to those reported by Cuevas (2002) for Chilean Tierra del Fuego, where 29–57% was browsed. Despite recruitment seeming to be guaranteed, the browsing impact must be taken into account in the forest management, as it restricts growth to the adult tree stage and promotes bad tree stem formation that depreciates the timber value. In this way, it is remarkable the role played within the forest by tree harvesting residuals as a physical protection for young seedlings (Pulido et al., 2000). *"Lote 73*" was the only MU with no sampled regeneration. It is located within the ecotone between the forest and the Patagonian steppe, where livestock (mainly cattle and sheep) grazing is the main productive activity. This MU exhibited the highest extraction intensity (75% in BA, Fig. 3) and it was the only MU where the windblown timber and the harvesting residuals had been removed. Overgrazing and uncontrolled browsing are the main menace to forest recruitment, as in many other forest ecosystems around the world (Agestam et al., 2003).

It is possible to find several clearcut areas in Tierra del Fuego, although clearcutting was not considered in the studied MUs. Several of the forest management plans selected ("*Tierra Mayor II*" and "*Vega Café*") prescribed clearcut interventions. However, the implementation of selective cuttings were conducted by sawmills in these stands independently on the designed harvesting plan by the forest administration. Additionally, the plots sampled closer to the main roads were the most intensely harvested, due to the firewood extractions in the oldest MUs. In the 1990s, the shelterwood system was not properly applied. The maximum and minimum values of BA felled were in correspondence with the limits established by the prescribed shelterwood system. Nevertheless, the objective of the first cut of this system was not accomplished. The harvested DBHs and log qualities extracted suggest the existence of an intensive selection among the best trees and, hence, an impoverishment of the residual structure. The economical interest of sawmills has prevailed over the sustainable management of these stands. Thus, neither an enhancement over the residual forest structure nor a complete silvicultural system is implemented, but a selective cutting more restricted in the BA felled limits.

Apart from the exceptions cited, regeneration was successfully established in the managed stands. However, the successful regeneration of the harvested stands is not enough to achieve forest sustainability (Schmidt and Urzúa, 1982; Martínez Pastur et al., 2000). In the present case it is not possible to obtain any economical benefits directly from the current impoverished forest structure. The unevenly implemented harvesting has resulted in a complex irregular mixture of stands of untouched forest with others under different levels of harvesting intensity. These are badly distributed, with a low tree density, and low potential log under bark volumes. Recruitment is generally guaranteed, but also distributed on an irregular pattern. As a consequence, this current structure is extremely complicated to manage through future intermediate treatments. The conversion of the primary forest stands to a regular managed and more profitable structure has not been performed, in spite of being in theory the main goal of the proposed silvicultural methods (Schmidt and Urzúa, 1982; Martínez Pastur et al., 2000). Moreover, the current incomplete application has resulted in a more irregular and less valuable forest structure than the primary one. However, these *Nothofagus* forests are easy to manage, due to their monospecific composition and the absence of problems in recruitment that other warmer (Dickinson et al., 2000; Hall et al., 2003) and temperate forests (Kozlowski, 2002; Agestam et al., 2003; Rozas, 2003) exhibit.

A complete silvicultural plan along with reduced-impact logging methods would improve this situation in the future. It must be emphasised that the damage produced over the remaining forest structure and browsing are the major impacts received by these forests. Lindenmayer (1999) supports that cumulative effects in logged forests are the most difficult to assess, especially where evidence of human perturbation is recent, as is the case of the Argentine portion of Tierra del Fuego. For this reason, post-harvesting monitoring of changes in biodiversity and harvesting consequences, in the way described by Neyland and Cunningham (2004), must be performed in the future. This will assure the assumption of appropriate management decisions in searching for the economic and ecological sustainability of these forests.

5. Conclusions

Changes in the forest management and forest policies during the last four decades have neither affected the timber extraction yields, nor improved silvicultural status of the stands harvested in Tierra del Fuego (Argentina). The prescribed management has not actually been achieved. Harvesting becomes more aggressive through the years, showing the lack of an appropriate control regime by the national and provincial forest administrations along with the indifference of the sawmills and ranch owners for the future of the forest resource. The damage of the residual forest structure has never been taken into account, windthrow being the most important problem of the harvested stands. Large volumes of timber were wasted, due to the implementation of incomplete silvicultural procedures and the inappropriate use of the skidders during the harvesting. On the other hand, uncontrolled sheep and cattle browsing represent the other main threat for the future of the forests, especially those located in ecotonal areas.

Nevertheless, the resilience of these ecosystems ensures abundant and proper recruitment in the harvested stands, if overgrazing is avoided. The incomplete silvicultural practices applied to the stands produce an irregular structure where regeneration is patchily distributed. The result is a forest with low market value and an excessive irregularity, less valuable than the primary forest or the potential managed forest structure. The current structure of the harvested stands needs to be reconverted into a more profitable one, which could enable both the economic and ecological sustainability of such a valuable resource. To achieve this goal, an overall forest management plan for Argentine Tierra del Fuego must be developed, including a complete silvicultural system applied by specialized workers. The performance of a sustainable forest management plan should be easier in these ecosystems than in many others of the world, due to: (a) the stands are mostly monospecific and have more easily predictable dynamics than other forests (Veblen, 1989; Pollmann, 2002); (b) the general successful establishment of regeneration; this would make it only necessary to guarantee forest recruitment, the exclusion of cattle and the control of native *Lama guanicoe* populations where it has been mentioned elsewhere; (c) the low human population density in the forested areas; (d) the availability of enough management tools derived from the knowledge already acquired (i.e. Schmidt and Urzúa, 1982; Martínez Pastur et al., 2002b); and (e) the inherent ecological characteristics of these ecosystems, that as it has been demonstrated can be compatible with management and biodiversity preservation (Spagarino et al., 2001; Deferrari et al., 2001; Martínez Pastur et al., 2002a).

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