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# Timber management with variable retention in *Nothofagus pumilio* forests of Southern Patagonia

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## ABSTRACT

Forestry practices integrating ecological and social criteria have been replacing those based only on economic values. Traditional silviculture, such as shelterwood cuts (*SC*), transforms uneven-aged original stands to an even-aged managed forest. Recently, other methods have proposed to conserve some of the original heterogeneity of the old-growth forests. One proposal leaves 30% of the timber quality forest area as aggregated retention and 20% basal area as dispersed retention. The aim of this study was to analyze the feasibility of timber management with aggregated and dispersed retention in *Nothofagus pumilio* old-growth forests by analyzing timber and harvesting yield potential compared with traditional regeneration systems. Also, remnant tree stability of aggregated retention was analyzed.

Timber yield potential of old-growth forests varied from 136 to 479 $m^3 ha^{-1}$ across a site quality gradient. High grading cutting improved yield index (timber volume and harvested basal area (*HBA*) ratio of 7.9 $m^3 m^{-2}$). In contrast, this index decreased in clear-cuts (4.7 $m^3 m^{-2}$) and shelterwood cuts (4.9 $m^3 m^{-2}$). The index also decreased in the aggregated and dispersed retention treatment (5.1 $m^3 m^{-2}$), but with higher timber harvested volumes. Windthrow of remaining trees in aggregated retention was related to time, being significantly higher during the first year after harvesting. Windthrow was affected by crown class and position into the aggregates of the remnant trees as well as site quality of the stand.

Regeneration methods with aggregated retention were feasible across the entire site quality gradient, and economic losses were not significant when compared to shelterwood cuts. The method also resulted in stability of the remnant overstory, which maintained the ecological conditions to ensure biodiversity conservation and continuity of harvested stands.

## 1. Introduction

Historically, natural forests designated for timber production have been mainly managed using economic criteria (McComb et al., 1993; McClellan et al., 2000). In the Northern Hemisphere, most old-growth forests have been transformed into single-species stands with a more regular structure (e.g., Oliver and Larson, 1996). Similar changes are occurring in Southern Patagonian forests (Martínez Pastur et al., 2000; Gea et al., 2004). Most silvicultural practices encourage this transformation from uneven-aged natural forest to even-aged managed forest via natural regeneration from seeds in the harvested stands (Schmidt and Urzúa, 1982). *Nothofagus pumilio* is a mid-tolerant shade species (Martínez Pastur et al., 2007a). Forests dominated by this species have been regenerated using various methods, including high grading cuttings, clear-cuts (*CC*) or shelterwood cuts (*SC*) (Schmidt and Urzúa, 1982; Martínez Pastur et al., 1999; Gea et al., 2004; Rosenfeld et al., 2006). These traditional silvicultural practices (e.g., shelterwood cuts) significantly affected the original diversity of flora and fauna in these forests (Pulido et al., 2000; Deferrari et al., 2001; Spagarino et al., 2001; Martínez Pastur et al., 2002a; Ducid et al., 2005). Consequently, ecological and social criteria are being increasingly prioritized over economic values alone, as the basis for their future management (Mitchell and Beese, 2002; DeBell and Curtis, 1993). As a result, alternative silvicultural methods are being proposed and must be evaluated. The replacement of traditional by alternative silvicultural practices at landscape scale also requires analyses of their economic feasibility by studying (a) potential changes in timber yields across a site quality gradient, (b) the costs of their implementation,

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(c) the success of establishment of natural regeneration, and (d) changes in biodiversity.

One alternative practice designed to conserve the original biodiversity and at least part of the original heterogeneity of the natural old-growth forest leaves 30% of the harvested area as aggregated retention and 20% of the basal area as dispersed retention (Martínez Pastur and Lencinas, 2005; Vergara and Schlatter, 2006; Martínez Pastur et al., 2007b; Lencinas et al., 2007, 2008). Implementation of this practice, known as variable retention, at large scale has been feasible in Tierra del Fuego. Compared to traditional silviculture, it was found that increased yield losses due to the overstory retention were compensated by decreased harvesting operation costs (Martínez Pastur et al., 2007b). A preliminary analysis also showed that the conservation of biodiversity and maintenance of ecological cycles were improved (Lencinas et al., 2007; Martínez Pastur et al., 2007b).

This study examines timber management using aggregated and dispersed retention in *N. pumilio* forests of Southern Patagonia. Firstly, timber yield potential of old-growth forests was analyzed to determine (a) the quantity and quality of saw logs, and (b) the feasibility of utilizing logs from across all site qualities in the sawmill industry. Secondly, the quantity and quality of timber production across a site quality gradient was compared between traditional silvicultural systems using clear-cuts, high grading cuttings or shelterwood cuts and with aggregated and dispersed retention. Thirdly, regeneration methods including aggregates were examined from the perspective of remnant tree stability. The advantages of aggregated and dispersed retention are discussed in relation to timber management and ecosystem services.

## 2. Methods

### 2.1. Study site and forest structure characterization

A pure natural old-growth *N. pumilio* forest of 61 ha was selected in San Justo Ranch, Tierra del Fuego, Argentina (54°06′ S, 68°37′ W). This forest had a full range of site quality classes (*SQC*), and the site index at a base age of 60 years ($SI_{60}$) ranged between 9.8 and 23.2 m height. Stands growing in *SQC I* ($SI_{60}$ = 19.8–23.2 m height) have a total volume of more than 1100 $m^3\,ha^{-1}$, in *SQC II* ($SI_{60}$ = 16.5–19.8 m height) have 900–1100 $m^3\,ha^{-1}$, in *SQC III* ($SI_{60}$ = 13.1–16.5 m height) have 700–900 $m^3\,ha^{-1}$, in *SQC IV* ($SI_{60}$ = 9.8–13.1 m height) have 550–700 $m^3\,ha^{-1}$ and in *SQC V* ($SI_{60} = < 9.8$ m height) less than 550 $m^3\,ha^{-1}$ (Martínez Pastur et al., 1997, 2000; Gea et al., 2004).

Weather conditions were measured in the study area with two weather stations (Weather Wizard III and accessories, Davis Instruments Corp., USA) placed from 2002 to 2005 in an old-growth forest and in a dispersed retention harvested stand (Martínez Pastur et al., 2007b). Climate was characterized by short, cool summers and long, snowy and frozen winters. Mean monthly air temperatures (2 m height from the forest floor) varied from $-0.2$ to 10.4 °C (minimum and maximum temperature of $-9.6$ °C in July and 24.9 °C in February, respectively) in the old-growth forest, while in the harvested stand these variables varied from $-1.0$ to 10.6 °C (minimum and maximum temperature of $-11.3$ °C in July and 25.9 °C in February, respectively). Only 3 months per year were free of mean daily temperatures under 0 °C, and the growing season was approximately 5 months (Barrera et al., 2000). Daily soil temperature at 30 cm depth remained $>0$ °C in the old-growth forest, but was $<0$ °C in the harvested stand ($-0.2$ to $-0.6$ °C during June–July). Rainfall, including snowfall, at 2 m height from the forest floor was 382 mm $year^{-1}$ inside the old-growth forest and 639 mm $year^{-1}$ in the harvested stand. Annual average wind speed outside forests was 8 km $h^{-1}$, reaching up to 100 km $h^{-1}$ during storms.

The original forest structure was characterized prior to harvesting across *SQC* via 40 random circular plots of 500 $m^2$ ($n = 8$ per *SQC*) measuring tree height (*H*), tree density (*N*), quadratic mean diameter (*QMD*), basal area (*BA*), stand density index (*SDI*), ratio of total over-bark volume (*TOBV*) and *BA*, and ratio of under-bark timber volume (*UBTV*) and *BA* (for equations and methodologies see Martínez Pastur et al., 2000, 2002b). The data were analyzed using one-way *ANOVA* with *SQC* as the main factor. Significantly different means were separated with a post hoc Tukey test ($p < 0.05$).

### 2.2. Model prediction of under-bark timber volume in old-growth forests

Overstory trees in the 40 plots were identified with numbered tags and felled with a chainsaw. Diameter and length of saw logs were measured and classified according to the log quality classification proposed by Cordone and Bava (1997) (*LQA* = logs without defects, *LQB* = logs with minor defects, *LQC* = logs with local defects or bad form, *LQD* = logs with generalized defects and bad form). The Smalian formula (Husch et al., 2003) was used to estimate log volume.

A model to predict *UBTV* at stand level was fitted using harvested basal area (*HBA*) and *SQC* as independent variables. This model simulated different regeneration systems in the harvesting of old-growth forests. Data of timber yield and forest structure at stand level were obtained from the same 40 inventory plots. Twenty-five simulations were carried out on each plot. Trees were selected step-by-step according to their timber log volume. For example, each tree from the plot was ordered according to their *UBTV*, such that the first trees to be included in the simulation were those that presented the higher individual values. Non-linear regression techniques were used to fit pairs of data (*UBTV* and *HBA*) ($n = 1000$). Adjusted *R*-squared ($r^2$-*adj*), standard error of estimation (*SEE*) and mean absolute error (*MAE*) were used to evaluate model fitness.

### 2.3. Regeneration system simulations

Four regeneration systems were analyzed: (a) *CC*, where all trees in the harvested stand were included; (b) a *SC*, where all trees were considered except 30 $m^2\,ha^{-1}$ basal area of the most dominant trees that were reserved as remnant basal area according to the Local Forest Office regulations (Schmidt and Urzúa, 1982; Martínez Pastur et al., 2000); (c) aggregated (one circular island per hectare of original forest with 30 m radius) and dispersed retention (15 $m^2\,ha^{-1}$ basal area of the most dominant trees distributed between aggregates) (*INT*) (Martínez Pastur and Lencinas, 2005; Martínez Pastur et al., 2007b), where all the other trees were included; and (d) high grading cutting (*HG*), where only the most profitable trees were harvested (individual trees with a yield up to 0.5 $m^3$ of the better quality logs). In each of the described plots, the trees to be included in each regeneration system were defined in field with qualified personnel before harvesting. Yield quantity and quality of saw logs for each plot were obtained after harvesting for all the described regeneration treatments. Yield quantity and quality of the plots were compared using regeneration systems and *SQC* as main factors in a two-way *ANOVA*. Significantly different means were separated with a post hoc Tukey test ($p < 0.05$).

### 2.4. Remnant tree stability in the aggregated retention

Permanent plots were established to determine remnant tree stability of aggregated retention. There were two treatments: (i) aggregated retention with dispersed retention (*INT*) (10.7 ha), and (ii) aggregated retention with clear-cuts between aggregates (*AR*)

(18.5 ha). Ten aggregates of each treatment were established during the summer of 2001. To quantify tree stability during the first 6 years after harvesting, windthrown trees were counted annually by measuring their *QMD*, *H*, crown class, fall angle and location within the aggregate. To determine their location, the aggregate area was divided in three sectors: (a) *inside*, radius of 17.3 m from the center of the aggregate; (b) *middle*, radius of 17.3–24.5 m; and (c) *outside*, radius of 24.5–30.0 m. Repeated measures *ANOVA* of windthrown *BA* and *TOBV* were carried out using treatment (*INT* and *AR*) and location (inside, middle and outside) as main factors. A comparative analysis was performed between windthrown trees into the permanent plot and the forest structure of an old-growth unmanaged forest: (a) height-to-diameter ratio, comparing the original forest structure prior to harvesting and the ratios of windthrown trees; (b) crown class (dominant, codominant, intermediate and suppressed), comparing the distribution in the stand prior to harvesting and the crown classes of windthrown trees; (c) quadrant in the aggregates were windthrow occurred; and (d) orientation of individual windthrown trees compared to those in an old-growth forest without management. Wind speed was not measured at overstory crown level. Therefore, the analysis assumed that wind intensity was equal throughout the 6 studied years. Extreme windthrow events, as those described by Rebertus et al. (1997), were not observed during the study period.

## 3. Results

### 3.1. Timber yield potential of old-growth forests

There were significant differences in *TOBV* and *UBTV* across the *SQC* gradient (Table 1). Thus, *H* and *QMD* decreased and *N* increased from *SQC I* to *SQC V* stands. There were significant differences in *BA* and *SDI*. Lower *BA* was observed in *SQC I* and *II* due to presence of larger gaps, while a higher degree of occupation was found in worse *SQC* stands due to higher tree densities. Better *SQC* stands had more *TOBV* and *UBTV* in diameter classes of 50–60 cm, while worse *SQC* stands had a wider range of diameter classes not exceeding 30–40 cm (Fig. 1). *UBTV* was greater in stands with higher than lower *SQC*. The distribution of stand volume against diameter size varied across the *SQC* (Table 1 and Fig. 1). In *SQC I* to *III* the diameter distribution appeared normal, while in *SQC IV* and *V* the distribution was skewed towards the smaller size classes that were related to a simultaneous increase in *N* and *SDI*. Both *TOBV*/*BA* and *UBTV*/*BA* indexes decreased significantly as *SQC* decreased (15.4–6.7 $m^3\ m^{-2}$ and 7.9–2.1 $m^3\ m^{-2}$, respectively) (Table 1).

Log quality classes of *UBTV* varied across the *SQC*. Logs without defects decreased significantly from 25.9% to 7.3% between *SQC I* and *V*. Conversely, the logs in the poorest quality class (*LQD*) increased significantly from 7.4% to 27.3% between *SQC I* and *V* (Fig. 2). The proportion of small diameter logs (<30 cm diameter) significantly increased from 13.5% to 50.1% between *SQC I* and *V* (Fig. 2).

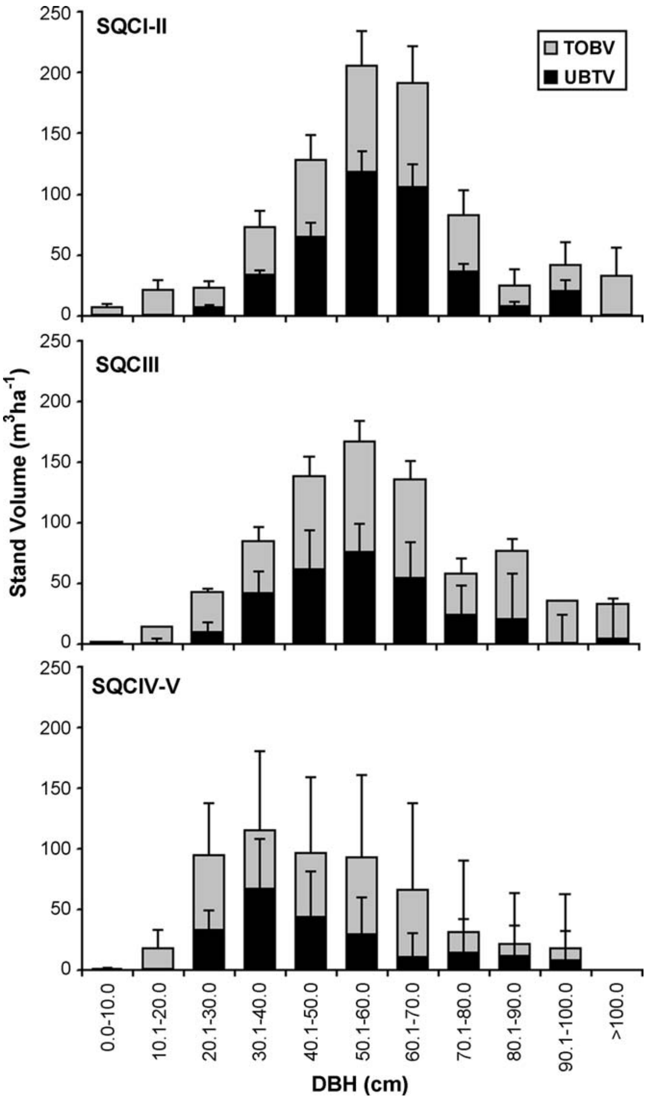

**Fig. 1.** Histograms of stand volume as a function of diameter at breast height (*DBH*) across the site quality classes (*SQC*), where *I*–*II* = high quality, *III* = medium quality, *IV*–*V* = low quality (see text and Martínez Pastur et al., 1997). *TOBV* = total over-bark volume; *UBTV* = under-bark timber volume. Bars represent ± standard error.

*UBTV* ($m^3\ ha^{-1}$) was predicted by the following equation:

$$UBTV = a(6 - SQC)^{b} HBA^{c} \tag{1}$$

where *SQC* = site quality class (*I*–*V* in Arabic numbers), *HBA* = harvested basal area ($m^2\ ha^{-1}$), and the adjustment parameters were $a$ = 9.479760, $b$ = 0.678100 and $c$ = 0.667798.

**Table 1**

Forest structure of old-growth stands across site quality classes (*SQC*). The variables measured were: dominant height (*H*), density (*N*), quadratic mean diameter (*QMD*), basal area (*BA*), stand density index (*SDI*), ratio of total over-bark volume and basal area (*TOBV*/*BA*) and ratio of under-bark timber volume and basal area (*UBTV*/*BA*).

| *SQC* | *H* (m) | *N* (trees $ha^{-1}$) | *QMD* (cm) | *BA* ($m^2\ ha^{-1}$) | *SDI* (%) | *TOBV*/*BA* ($m^3\ m^{-2}$) | *UBTV*/*BA* ($m^3\ m^{-2}$) |
|---|---|---|---|---|---|---|---|
| *I* | 28.3e | 312a | 46.9b | 60.6ab | 76.6ab | 15.4e | 7.9c |
| *II* | 25.5d | 425a | 36.7ab | 57.4a | 66.4a | 13.5d | 5.9bc |
| *III* | 22.9c | 471a | 40.6ab | 69.3ab | 81.8ab | 11.9c | 4.2ab |
| *IV* | 18.7b | 595ab | 36.4ab | 74.7b | 83.8ab | 9.3b | 3.8a |
| *V* | 14.5a | 834b | 29.5a | 64.8ab | 92.9b | 6.7a | 2.1a |
| *F* | 160.6 | 8.3 | 3.9 | 3.6 | 2.8 | 114.4 | 14.5 |
| *p* | <0.001 | <0.001 | 0.010 | 0.016 | 0.039 | <0.001 | <0.001 |
| d.f. | 40 | 40 | 40 | 40 | 40 | 40 | 40 |

*F* = Fisher test, *p* = significance, d.f. = degrees of freedom. Different letters indicate significant differences by Tukey test at $p < 0.05$. Site quality classes (*I*–*V*) (see text and Martínez Pastur et al., 1997).

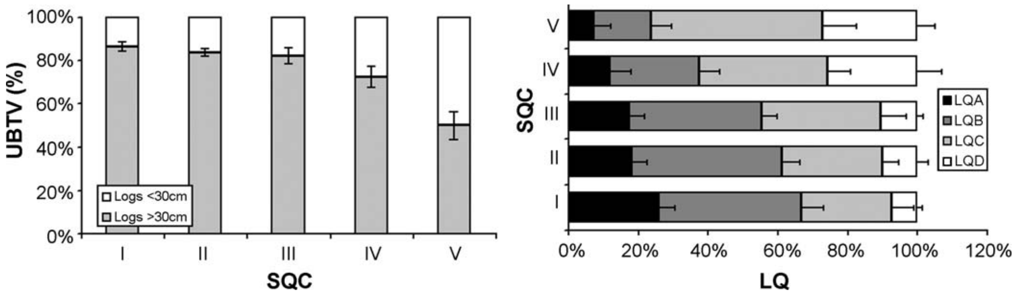

**Fig. 2.** Log size and log quality (*LQ*) of under-bark timber volume (*UBTV*) across the site quality classes (*SQC*). Bars represent ± standard error. For log quality classification (*A–D*) and site quality classes (*I–V*) see text, Cordone and Bava (1997) and Martínez Pastur et al. (1997).

Adjusted *R*-squared ($r^2$-*adj*), *SEE* and *MAE* were 73.22, 66.51 and 46.59, respectively. The proposed model was best represented by polymorphic curves that have a higher slope during the harvesting of the first 10–20 $m^2\ ha^{-1}$ of *HBA*. Changes in slope then decreased markedly with further increases in *HBA*. *UBTV* increased proportionally with *SQC* of the stands, but decreased in the worst *SQC*, e.g., when 40 $m^2\ ha^{-1}$ *HBA* was harvested, *UBTV* yield reached up to 332, 285, 235, 178 and 111 $m^3\ ha^{-1}$ for *SQC I–V*, respectively.

### 3.2. *Timber production of different regeneration systems across a SQC*

Significant differences were found for all variables measured when different regeneration systems were compared across the *SQC* gradient (Table 2). High grading cutting (*HG*) only considered the harvesting of a small percentage of trees (12% of the trees of the stand), which represented 18% of the total *BA* of the stand. This harvesting method maximized log yield (7.9 $m^3\ m^{-2}$ *UBTV*/*BA*) obtaining the most favorable ratio between low and high quality log volume (23% *LQC* + *LQD*/*LQA* + *LQB*). However, the subsequent regeneration method left a high quantity of slash material in the stand which could be a potential *UBTV* (69%). Shelterwood cuts (*SC*) considered the harvesting of 52% of the stand *BA*, cutting 80% of the trees. The remnant structure was composed by large trees with good potential seed production and a favorable ratio of height-to-diameter (less than 0.7). In this method, yield of harvested logs was low (4.9 $m^3\ m^{-2}$ *UBTV*/*BA*) with higher percentage of lower quality logs (78% *LQC* + *LQD*/*LQA* + *LQB*). Aggregated retention with dispersed retention method (*INT*) considered the harvesting of 50% original stand *BA* by cutting less trees (61%) than *SC*. Yield of harvested logs (5.1 $m^3\ m^{-2}$ *UBTV*/*BA*) and ratio between low and high quality log volume (72% *LQC* + *LQD*/*LQA* + *LQB*) were similar to those obtained through *SC*. *CC* did not significantly changed yield of harvested logs (4.7 $m^3\ m^{-2}$ *UBTV*/*BA*) and the ratio between low and high quality log volumes (75% *LQC* + *LQD*/*LQA* + *LQB*) when they were compared with the two previously evaluated regeneration systems.

When *SQC* range was analyzed as the main factor, significant differences were found in all variables except in low quality log (*LQD*) yields (Table 2). As expected, the best *SQC* stands had higher yields of better quality logs than the worst *SQC* stands (Fig. 2). Most of the significant interactions were due to *HG* treatment, where the harvested values of this treatment were higher in the best *SQC* and lower in the worse *SQC* stands when they were compared to *INT* and *SC* treatments. Thus, *HG* was not feasible in *SQC IV–V* stands, due to the low yield (*UBTV* of 16–64 $m^3\ ha^{-1}$ in full stocked stands). However, *SC* and *INT* made it possible to harvest these worst *SQC* stands (81–181 and 78–160 $m^3\ ha^{-1}$, respectively). These differences between treatments declined in the best *SQC* stands (158, 234 and 233 $m^3\ ha^{-1}$ of *UBTV*, 15, 28 and 28 $m^2\ ha^{-1}$ of *HBA* for *HC*, *SC*, and *INT* treatments, respectively), where *HC* carried out more intensive cuts compared to the worst *SQC* (e.g., 3 $m^2\ ha^{-1}$ *HBA* was harvested in *SQC V*).

### 3.3. *Remnant tree stability in the aggregated retention*

There were no significant differences in *BA* and *TOBV* of windthrown trees between aggregated retention (*INT* and *AR*) treatments or locations within the aggregate (inside, middle or outside) (Table 3). There were differences when time of harvesting was analyzed. Windthrown *BA* and *TOBV* were significantly higher during the first year after the harvesting (0.7–1.8 $m^2\ aggregate^{-1}$ *BA* and 7.9–22.4 $m^3\ aggregate^{-1}$ *TOBV*) than in the following years

**Table 2**

Harvested trees (*N*), harvested basal area (*HBA*), total over-bark volume (*TOBV*), under-bark timber volume (*UBTV*) and log quality volume (*LQA* to *LQD*) considering regeneration systems and site quality classes as main factor analysis.

| Main factors | *N* (trees $ha^{-1}$) | *HBA* ($m^2\ ha^{-1}$) | *TOBV* ($m^3\ ha^{-1}$) | *UBTV* ($m^3\ ha^{-1}$) | *LQA* ($m^3\ ha^{-1}$) | *LQB* ($m^3\ ha^{-1}$) | *LQC* ($m^3\ ha^{-1}$) | *LQD* ($m^3\ ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| *HG* | 64a | 11.8a | 148.7a | 93.0a | 25.6a | 50.0a | 15.9a | 1.5a |
| *INT* | 322b | 32.6b | 362.9b | 164.9b | 25.6a | 70.0a | 54.4b | 14.9b |
| *SC* | 423c | 33.6b | 374.1b | 165.4b | 19.8a | 73.2a | 55.7b | 16.7b |
| *CC* | 528d | 65.0c | 727.8c | 304.2c | 46.0b | 127.6b | 100.7c | 29.8c |
| *I* | 199a | 33.1ab | 508.1d | 273.6c | 59.6c | 117.2c | 79.3c | 17.4 |
| *II* | 278ab | 30.9a | 425.1bc | 194.9b | 30.2b | 83.9b | 63.9bc | 16.9 |
| *III* | 302ab | 39.1bc | 470.3cd | 189.9b | 37.2bc | 97.0bc | 44.5ab | 11.3 |
| *IV* | 381b | 42.1c | 387.6b | 172.7b | 16.7ab | 67.3b | 67.5bc | 21.2 |
| *V* | 511c | 33.6ab | 225.7a | 78.3a | 2.6a | 35.5a | 28.2a | 11.9 |
| $F_{\text{reg.system}}$ | 72.3 (<0.001) | 231.7 (<0.001) | 187.6 (<0.001) | 46.3 (<0.001) | 6.9 (<0.001) | 20.8 (<0.001) | 27.2 (<0.001) | 13.0 (<0.001) |
| $F_{\text{site class}}$ | 18.8 (<0.001) | 9.2 (<0.001) | 28.9 (<0.001) | 19.8 (<0.001) | 13.8 (<0.001) | 13.0 (<0.001) | 7.0 (<0.001) | 1.3 (0.278) |
| Interactions | 3.2 (<0.001) | 2.3 (0.009) | 1.9 (0.041) | 1.4 (0.199) | 1.3 (0.227) | 1.0 (0.494) | 0.5 (0.932) | 0.3 (0.994) |
| d.f. | 160 | 160 | 160 | 160 | 160 | 160 | 160 | 160 |

*F*(*p*) = Fisher test and significance between brackets, d.f. = degrees of freedom. Different letters indicate significant differences by Tukey test at $p < 0.05$. For log quality classification (A–D) and site quality classes (I–V) see text, Cordone and Bava (1997) and Martínez Pastur et al. (1997). *HG* = high grading cutting; *INT* = aggregated and dispersed retention; *SC* = first intervention of a shelterwood cut; *CC* = clear-cuts.

**Table 3**
Repeated measures ANOVA and means for regeneration treatments (aggregated retention with clear-cuts – *AR*, or aggregated retention with dispersed retention – *INT*) and tree location in the aggregate (inside, middle or outside) for windthrown basal area (*BA*) and total over-bark volume (*TOVB*) per aggregate along the 6 first years after harvesting.

| Source | d.f. | *BA* | | *TOBV* | |
|---|---|---|---|---|---|
| | | *MS* | *F* (*p*) | *MS* | *F* (*p*) |
| Between subject effects | | | | | |
| Treatments | 1 | 0.94 | 3.73 (0.059) | 140.88 | 3.36 (0.072) |
| Locations | 2 | 0.27 | 1.10 (0.339) | 33.01 | 0.79 (0.460) |
| Within subject effects | | | | | |
| Years | 5 | 1.18 | 7.74 (0.001) | 172.47 | 6.91 (0.001) |
| Interactions | | | | | |
| Treatments × locations | 2 | 0.10 | 0.42 (0.660) | 19.55 | 0.47 (0.623) |
| Treatments × years | 5 | 0.27 | 1.79 (0.114) | 47.13 | 1.89 (0.096) |
| Locations × years | 10 | 0.24 | 1.56 (0.118) | 34.43 | 1.38 (0.189) |
| Treatments × locations × years | 10 | 0.03 | 0.19 (0.997) | 5.27 | 0.21 (0.995) |

| Years after harvesting | | *BA* (m$^2$ agregate$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| Treatment | Location | 1 | 2 | 3 | 4 | 5 | 6 |
| AR | Inside | 0.34 | 0.04 | 0.03 | 0.15 | 0.13 | 0.02 |
| | Middle | 0.61 | 0.14 | 0.16 | 0.10 | 0.08 | 0.13 |
| | Outside | 0.87 | 0.15 | 0.18 | 0.05 | 0.04 | 0.00 |
| INT | Inside | 0.10 | 0.00 | 0.00 | 0.00 | 0.07 | 0.13 |
| | Middle | 0.05 | 0.05 | 0.03 | 0.04 | 0.01 | 0.00 |
| | Outside | 0.53 | 0.15 | 0.15 | 0.00 | 0.03 | 0.01 |

| Years after harvesting | | *TOBV* (m$^3$ aggregate$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|---|
| Treatment | Location | 1 | 2 | 3 | 4 | 5 | 6 |
| AR | Inside | 4.07 | 0.55 | 0.33 | 1.98 | 1.77 | 0.24 |
| | Middle | 7.92 | 1.28 | 2.13 | 1.29 | 1.07 | 1.45 |
| | Outside | 10.45 | 1.55 | 2.17 | 0.55 | 0.38 | 0.00 |
| INT | Inside | 1.08 | 0.00 | 0.04 | 0.00 | 0.83 | 2.04 |
| | Middle | 0.64 | 0.33 | 0.27 | 0.36 | 0.17 | 0.00 |
| | Outside | 6.14 | 1.86 | 1.92 | 0.00 | 0.33 | 0.15 |

d.f. = degrees of freedom; MS = median square; *F* (*p*) = Fisher test and significance between brackets.

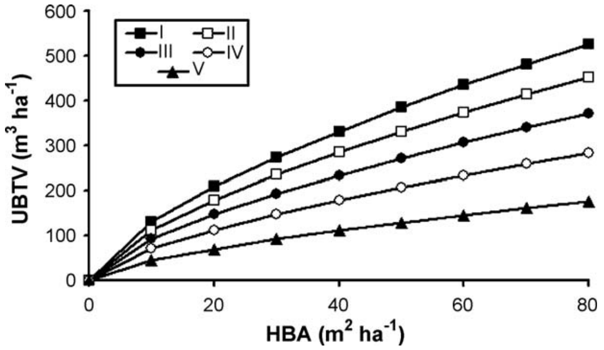

**Fig. 3.** Model prediction of under-bark timber volume (*UBTV*) related to harvested basal area (*HBA*) across the site quality classes (*I–V*) (see text and Martínez Pastur et al., 1997).

(0.04–0.4 m$^2$ aggregate$^{-1}$ year$^{-1}$ *BA* and 0.4–4.6 m$^3$ aggregate$^{-1}$ year$^{-1}$ *TOBV*).

The number of windthrown trees was higher in the sectors outside of the aggregates (1.8–1.7 times higher in *AR* and 2.9–2.6 times higher in *INT* for *BA* and *TOBV* compared to the inside sector). This effect was higher during the first 3 years and decreased over time. Tree age did not greatly influence windthrow in the harvested stands (33% of trees have less than 120 years, and 67% have more than 120 years), where similar values were found in the old-growth primary forests before the harvesting (23% compared to 77%, respectively). However, windthrow was influenced by *SQC*. In *AR* treatment, 161 tree falls were registered, where 59% of these corresponded to the better *SQC* (*I–II*), 31% to middle *SQC* and 10% to worse *SQC* (*IV–V*). While 62 tree falls were observed in *INT* treatment (54% of which occurred in better *SQC I–II* and 46% in middle *SQC* stands), no falls occurred inside the aggregates of *SQC IV–V* (Fig. 3).

A comparison between windthrown trees in the *AR* and *INT* treatments and old-growth forest prior to harvesting showed that (Fig. 4): (a) height-to-diameter ratio was similar; (b) windthrow was higher in intermediate and suppressed tress compared to dominant and co-dominant trees; (c) windthrow was influenced

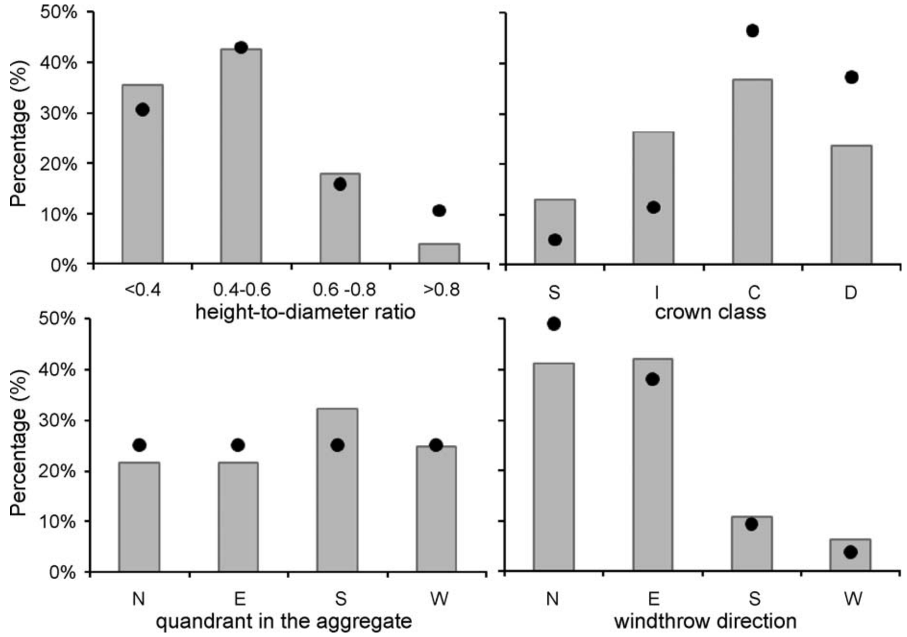

**Fig. 4.** Height-to-diameter ratio, crown class (suppressed-*S*, intermediate-*I*, codominant-*C*, dominant-*D*), position of the trees into the quadrants of the aggregates and windthrow direction comparison between observed values in the primary old-growth forests prior to harvesting (●) and the measured windthrown trees in the studied treatments (bars).

by position in the aggregate with more trees falling in the south and west quadrants; and (d) more windthrown trees fell in a north and east direction, with a similar trend with the old-growth forest prior to harvesting.

## 4. Discussion

### 4.1. Timber yield potential of old-growth forests

Forest structure varied with *SQC*, thus affecting the main variables related to forest yield. Biometric values recorded across the full *SQC* gradient of old-growth stands were similar to those described for other *N. pumilio* forests without previous management (Schmidt and Urzúa, 1982; Martínez Pastur et al., 2000; Gea et al., 2004). It has been shown that stands of similar age and of the same *SQC*, may have different stand density due to their intrinsic dynamics (e.g., rate of gap formation) (Veblen, 1989). For this reason, the ratio of volume/basal area was used in this study to make realistic comparisons between stands (Martínez Pastur et al., 2000). This ratio has been used previously in biometric models of *Nothofagus* forests (Martínez Pastur et al., 2002b).

The quality of timber logs obtained from harvesting varied with *SQC*. Such knowledge is essential for forest management planning at the landscape level due to the fact that log quality could determine the harvesting method and the industrial use of saw log products (Martínez Pastur and Lencinas, 2005). Large logs (up to 40 cm diameter) with the best yield in high quality saw log are mainly found in the better *SQC* stands, while in worse *SQC* stands the harvested logs are smaller (<30 cm) with a greater percentage of logs with undesirable defects (Martínez Pastur et al., 2000). Knowledge of the distribution of *SQC* at the landscape level can enable harvesting plans that incorporate stands with high and low timber yield (Martínez Pastur et al., 2007b).

During the last 40 years, *HC* was the most common harvesting system applied on Tierra del Fuego (Gea et al., 2004), based on the assumption that proportional stand saw log yield harvesting decreases when higher basal areas are cut. However, this was not observed in the present work, because stand saw log yield increased with harvesting intensity for the entire *SQC* gradient. It is possible, therefore, to apply more intensive harvesting and regeneration systems in fully stocked old-growth forests, maintaining the timber rates and decreasing the costs per harvested unit area (Martínez Pastur et al., 2007b).

### 4.2. Timber production of different silvicultural systems across SQC

Several industrial and experimental silvicultural systems have been used in Tierra del Fuego (Schmidt and Urzúa, 1982; Martínez Pastur and Lencinas, 2005; Bava and López Bernal, 2005; Rosenfeld et al., 2006). High grading cutting maximized harvest yield (*UBTV*/*BA*) by producing the best quality logs. This method increases harvesting costs (e.g., tree marking, forest management plans or road construction) and minimizes saw log yield. The method leaves a quantity of wasted potential logs in the stands that could have been used economically, and consequently large areas of forest to satisfy log demands are required. High grading cutting also results in excessive damage to remnant trees that could produce greater windthrow after the harvesting (McClellan et al., 2000; Gea et al., 2004).

Clear-cuts have also been applied in large areas of Tierra del Fuego (Gea et al., 2004), obtaining lower *UBTV*/*BA* harvesting ratios, due to the high percentage of small and low quality logs. The main advantage of this method was the high yield per unit area, making it economically feasible at large scale. However, the adoption of this approach at large scale raises societal concerns because it reduces the aesthetic value (McClellan et al., 2000) and biodiversity conservation of the forest (Hickey et al., 2001).

Shelterwood cuts increased the yield of harvesting compared to *HC* (Martínez Pastur et al., 2000) but with less saw log yield and greater associated logging costs. This system ensures the regeneration of the stands (Martínez Pastur et al., 1999; Rosenfeld et al., 2006), but significantly affects the original biodiversity (Deferrari et al., 2001; Martínez Pastur et al., 2002a), particularly insects (Spagarino et al., 2001). Other undesirable effects reported for this silvicultural system were the impacts on soil structure, seedlings (Saveneh and Dignan, 1997) and damage to the boles of retained trees during the harvesting (Hickey et al., 2001), which produce greater windthrow after logging (Gea et al., 2004). Finally, a reduction in harvesting efficiency occurs due to the need for careful maneuvering of machines and directional falling of trees (Hickey et al., 2001).

The silvicultural method with aggregated and dispersed retention maintains the same yield rates as the first cut of *SC*. Contrary to *SC*, *INT* reduces harvesting costs (Martínez Pastur et al., 2007b) and biodiversity loss (Lencinas et al., 2007, 2008). The main disadvantages were the loss of potential income through retention of trees with high quality logs, the occurrence of windthrow after harvesting in the dispersed retention, and the safety risks to personnel due to the presence of overhanging limbs and the risk of collisions between falling and retained trees (Hickey et al., 2001).

Aggregated and dispersed retention and *SC* allow the harvesting of the worse quality *SQC* stands. During the 1950s to 1970s, only *HG* and *CC* were applied in the better *SQC* stands of Tierra del Fuego (Gea et al., 2004). In contrast, harvesting of worse *SQC* occurred when *SC* was adopted (Gea et al., 2004) because yields were profitable (Martínez Pastur et al., 2000).

### 4.3. Remnant tree stability in the aggregated retention

Remnant overstory stability is one of the main concerns when a silvicultural treatment is applied. This is because canopy protection is needed to maintain regeneration and biodiversity and to avoid economic losses because of windthrow. Stand and ground characteristics, such as forest structure and previous management determine the critical wind speed at which wind damage occurs. Risk of wind damage varies between locations with different exposures and interactions between climatologic and topographic factors (Quine, 1995; Kellomäki and Peltola, 1999).

There were no significant differences in the windthrow risk between both regeneration aggregate treatments (*INT* and *AR*). Scott and Mitchell (2005) suggest that post-harvest density appears to be more important to windthrow risk than the pattern or type of retention employed. Windthrow intensity has also been cited to vary according to the retention levels and forest types. Montane Alternative Silvicultural Systems (Arnott and Beese, 1997) suffered damage of 10–29% *BA* in low retention levels (5–25% *BA*), which was consistent with data reported by Coates et al. (1997) (10–20% *BA*). In Demonstration of Ecosystem Management Options study (Aubry et al., 1999; Halpern et al., 1999), mortality increased with increasing levels of tree removal and was higher in dispersed than in aggregated retention treatments. Wind resistance varied with the species at different retention levels, as was cited by Beese (2001) for several species in 5–25% dispersed retention treatments.

In the regeneration systems with aggregated retention, the stability of the remnant overstory is crucial for biodiversity conservation, since it must remain for more than one forest rotation (Lencinas et al., 2007). A forest's capacity to resist dynamic wind loads increases due to the decrease in the height-to-diameter ratios of trees after thinning, and also due to the increase in strength and root mass. Thus, the risk peak for trees is during the first years following cuttings (Kellomäki and Peltola, 1999), as was observed in aggregate retention in this study. Greater windthrow occurs 1 year after the harvesting due to damage to the boles of retained trees in the harvested areas (Hickey et al., 2001), being the main cause of windthrow after logging (Gea et al., 2004). In XII Region (Chile), careful maneuvering of machines and directional falling avoids harming the remnant trees during the initial cuts of *SC*. However, damage due to harvesting of *SC* applied in Argentina produced windthrown trees that amounted up to 50% of remnant *BA* after a few years of logging (Gea et al., 2004). The risk of windthrow immediately after harvesting is also affected by the crown class. Dominant trees are less likely to suffer windthrow than lower crown class trees with higher height-to-diameter ratios and smaller root systems.

Crown classes of the remnant overstory, position of the trees in the aggregates and *SQC* of the stands also influenced over the windthown trees. Trees of the lower crown classes, trees located in the quadrants of prevailing wind direction (south and west for Tierra del Fuego) and in the higher *SQC* were more susceptible to being blown down, as also was reported for Rebertus et al. (1997). For this reason, one alternative to avoid windthrow risk would be using different amounts of dispersed retention between aggregates in proportion with *SQC* or wind exposure, since it can improve stand stability. New studies are needed to determine the increase of dispersed retention *BA* according to *SQC* or stands in aspects oriented to the prevailing wind directions.

### *4.4. Ecosystem advantages of timber management with aggregate retention in Southern Patagonia*

Regeneration systems that include different types of retention are intended to combine timber production with other forest values (DeBell and Curtis, 1993). *Nothofagus* is a classic Gondwanan genus that is quantitatively important in many southern landscapes (Monks and Kelly, 2006) and constitutes a significant portion of the last unmanaged forests in the Southern Hemisphere. Since the 1990s, even-age management with *SC* (Schmidt and Urzúa, 1982) has been the dominant silvicultural system used in Southern Patagonia (Gea et al., 2004) and is widely accepted as an economic and efficient method for timber production. However, even-age management has been criticized, due to the effects on other forest values such as the reduction of biodiversity (Deferrari et al., 2001; Spagarino et al., 2001; Martínez Pastur et al., 2002a).

Regeneration systems with aggregate and dispersed retention help to maintain ecosystem health, resilience and productivity, as well as compositional, structural, and functional diversity of old-growth forests (McClellan et al., 2000). These systems can also produce a sustainable supply of timber, thus combining economic and conservation outcomes which are biologically and socially acceptable (Martínez Pastur et al., 2007b). This study measured the potential timber yield of old-growth *N. pumilio* forests and has demonstrated the feasibility of applying a regeneration method with aggregated and dispersed retention that can capture industrial products across all site qualities. Remnant overstory trees inside the aggregates were maintained during the first years after the harvesting, enhancing the biodiversity conservation (Lencinas et al., 2007); however, new landscape management designs must be used that also minimize windthrow risks. The retention system proposed here for Southern Patagonia satisfies the need for a new silvicultural system by simultaneously maintaining biological diversity, as well as economic feasibility for the industry (Mitchell and Beese, 2002).

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