Retention forestry in southern Patagonia: multiple environmental impacts and their temporal trends

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SUMMARY

Harvesting with variable retention (VR) applied in *Nothofagus* forests combines two types of retention: patches of original forest (aggregates) and single isolated homogeneously distributed trees (dispersed). This study assesses the assumption that VR maintains mature forests conditions after harvesting by synthesizing 605 individual results from long-term studies in two regions of Tierra del Fuego (Argentina) with permanent monitoring. VR effects on (i) forest structure, (ii) microenvironment, (iii) biodiversity, and (iv) forest reproduction, were investigated. Aggregated retention had no effect on forest structure and microenvironmental variables, but increased biodiversity variables and forest reproduction compared to unmanaged primary forest (control). Dispersed retention negatively affected the forest structure, increased biodiversity, but did not affect microclimate and forest reproduction when compared to primary forest. Thus, the ecological conditions of *N. pumilio* forests are influenced by variable retention harvesting, but direction and magnitude of the effect depend on the treatment and differ among groups of variable. Inside aggregates several primary forest components and conditions were maintained.

Keywords: aggregated retention, biodiversity, forest management, mature forests, *Nothofagus*

Foresterie de rétention dans la Patagonie du sud: impacts environnementaux multiples et leurs courants temporels

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La récolte à rétention variable (VR) appliquée aux forêts *Nothofagus* combine deux types de rétention: des sections de forêt originale (agrégats) et des arbres isolés distribués avec homogénéité (dispersés). Cette étude évalue que la VR maintient des conditions de forêt mûres après la récolte, en synthétisant 605 résultats individuels d'études à long terme dans deux régions sous surveillance permanente en Terre de feu (Argentine). Les effets de la VR sur (i) la structure forestière, (ii) le micro environnement, (iii) la biodiversité et, (iv) la reproduction de la forêt ont été investigués. La rétention en agrégats n'avait aucun effet sur la structure forestière et les variables micro environnementales, mais elle accroissait les variables de biodiversité et la reproduction de la forêt, comparée à la forêt primaire non gérée (contrôle). Par contre, la rétention dispersée affectait négativement la structure forestière, et accroissait la biodiversité, mais elle n'affectait pas le micro climat et la reproduction forestière, une fois comparée à la forêt primaire. Ainsi, les conditions écologiques des forêts *N. pumilio* sont influencées par la récolte à rétention variable, mais la direction et la magnitude de ces effets dépendent du traitement opéré, et diffèrent selon les groupes de variables. Plusieurs composites et conditions des forêts primaires étaient préservés au sein des agrégats.

Silvicultura de retención en el sur de la Patagonia: múltiples impactos ambientales y sus tendencias temporales

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El aprovechamiento con retención variable (RV) en los bosques de *Nothofagus* combina dos tipos de retención: bosquetes de bosque primario (agregada) y árboles individuales aislados distribuidos homogéneamente (dispersa). Este estudio evalúa la hipótesis de que la RV mantiene las condiciones de bosque maduro después del aprovechamiento, mediante una síntesis de 605 resultados individuales provenientes de diferentes estudios a largo plazo en dos regiones con monitoreo permanente en Tierra del Fuego (Argentina). Se investigaron los efectos de la RV en (i) la estructura del bosque, (ii) variables microambientales, (iii) la biodiversidad, y (iv) variables reproductivas del bosque. La retención agregada no tuvo efecto sobre la estructura del bosque y las variables microambientales, pero aumentó las variables de biodiversidad y de reproducción del bosque en comparación con los bosques primarios no manejados (control). La retención dispersa afectó negativamente a la estructura del bosque y aumentó la biodiversidad, pero no afectó al microclima o a la reproducción del bosque, en comparación con los bosques primarios. Por tanto, las condiciones ecológicas de los bosques de *N. pumilio* se ven influenciadas por el aprovechamiento con retención variable, pero la dirección y la magnitud del efecto dependen del tratamiento y difieren entre grupos de variables. Dentro de los agregados se mantuvieron varios de los componentes y las condiciones de los bosques primarios.

INTRODUCTION

Until recently, natural forests designated for timber production have mainly been managed following economic criteria (McComb *et al.* 1993). These traditional forest practices often failed to reach multiple sustainability objectives. Nowadays, ecological and social criteria are being increasingly prioritized, towards sustainable and integrative forest management (Lindenmayer 2009). In this context, alternative silvicultural systems have been proposed, being variable retention (VR) one of them (Franklin *et al.* 1997). Variable retention implies the intentional long-term retention of pre-harvest structures and organisms during the management of a forest stand, for: (i) maintaining and enhancing the provisioning of ecosystem services and biodiversity; (ii) increasing public acceptance of forest harvesting and usage options of these harvested forests in the future; (iii) enriching the structure and composition of the post harvest forest; (iv) achieving temporal and spatial continuity of key ecosystem elements and processes, including those needed by both early- and late-successional specialist species; (v) maintaining connectivity in the managed forest landscape; (vi) minimizing the off-site impacts of harvesting, such as on aquatic systems; and (vii) improving the aesthetics of harvested forests (Gustafsson *et al.* 2012).

Variable retention is increasingly implemented in many parts of the world (Fedrowitz *et al.* 2014). It is highly adaptable, with great variation in application, including the pattern and amount of retention, which reflects differences in the management objectives and forest types (Gustafsson *et al.* 2012, Lindenmayer *et al.* 2012). Since VR seeks to mimic natural processes and to maintain biological legacies from the mature forests (Franklin *et al.* 1997, Lindenmayer 2009), the effect of this silvicultural treatment can be optimally tested in simple systems where few influencing factors are present. For example, in forest ecosystems with low species-replacement rates, harvesting could impact by reducing species diversity; while in those ecosystems with high species-replacement rate, harvesting could increase diversity, masking the loss of species dependent on mature forests.

At the austral extreme of South America, Tierra del Fuego Island is shared between Chile and Argentina, and hosts the world's southernmost forested ecosystems. They constitute a significant portion of the last unmanaged forests in the southern Hemisphere and are one of the most pristine eco-regions on the planet (Mittermeier *et al.* 2003). *Nothofagus*, a classic Gondwanan genus, is quantitatively important in these landscapes (Monks and Kelly 2006), *N. pumilio* being the main component, sustaining the regional timber industry. These southern Patagonian forests are relatively simple ecosystems: predominantly pure stands, with relatively recent management history (since the 1940s), simple sequences of succession (few and predictable seral stages), natural dynamics associated with gaps, and low animal and plant species diversity (Veblen *et al.* 1996, Frangi 1999, Martínez Pastur *et al.* 2010). Thus, *N. pumilio* forests could be a particularly useful test case to implement and evaluate impacts of this kind of forest management practices.

Variable retention has been applied and studied in Tierra del Fuego since the year 2000, and it is being increasingly implemented on large areas of *N. pumilio* forests (approximately 2,500 ha to date). Here, the theoretical prescription includes two types of retention within the same harvested unit or stand (Martínez Pastur *et al.* 2009): patches of 30 m radius spaced 40 m from each other with retention of 30% of the basal area and the complete original forest structure (e.g. aggregated retention), and retention of isolated single homogeneously distributed trees (10–15% of the basal area) between aggregates (e.g. dispersed retention) (Martínez Pastur *et al.* 2007, 2009).

Until now the impact of VR has been assessed in several individual studies that used indicators such as: (i) flower, fruit and seed productions (Martínez Pastur *et al.* 2008, 2013), (ii) richness and density of birds (Lencinas *et al.* 2009), (iii) insects (Lencinas *et al.* 2014), (iv) mistletoes and epiphytic lichens (Soler *et al.* 2014), (v) forest regeneration and microclimatic conditions (e.g. Martínez Pastur *et al.* 2011a,b), and native versus alien plant species (e.g. Lencinas *et al.* 2008, 2011). In this paper, we synthesize in a multi-objective analysis all the available evidence regarding the ecological impact of VR silvicultural management in *N. pumilio* forests of Tierra del Fuego (Argentina). This endeavor is urgently required, considering that VR is being increasingly implemented in *Nothofagus* forests and around the world. This study determines: (i) whether conditions of unmanaged primary forests are maintained under variable retention, and how aggregates and dispersed retention comparably perform in conserving these unmanaged primary forest conditions, (ii) how the response differs among categories such as forest structure, microenvironment, biodiversity, and forest reproduction variables, and (iii) how the effects vary with time after harvesting, for instance due to a potential gradual recovery of the primary forest conditions or further impoverishment (c.f. Paillet *et al.* 2010, Gustafsson *et al.* 2012). This synthesis was based on primary studies from Tierra del Fuego (Argentina), however, the obtained results can assist in the understanding of other forest ecosystems managed with VR.

METHODS

Study area

As part of PEBANPA network (Biodiversity and Ecological Long-Term Plots in Southern Patagonia), two permanent research sites were established in *N. pumilio* forests located in the Argentinean part of Tierra del Fuego: San Justo Ranch (54°06'S, 68°37'W) with 50 ha harvested and established in 2001, and Los Cerros Ranch (54°18'S, 67°49'W) with 75 ha harvested since and established in 2004 (Martínez Pastur *et al.* 2010). These sites were the first VR areas of *N. pumilio* and thus our sample represented a complete data source, and can be considered as a model case for a widespread application of variable retention management in the forests of the region (Gustafsson *et al.* 2012). Within these sites, several studies have been carried out independently from each other along these last 14 years.

Climate in this part of Tierra del Fuego is 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 primary 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 are free of mean daily temperatures under 0°C, and the growing season lasts approximately 5 months (Barrera *et al.* 2000). Daily soil temperature at 30 cm depth remained >0°C in the primary forest, but was <0°C in the harvested stand (-0.2 to -0.6°C during June-July). Precipitation at 2 m height above the forest floor was 382 mm/year inside the primary forest and 639 mm/year in the harvested stand. Annual average wind speed outside forests was 8 km/h, reaching up to 100 km/h during storms (Martínez Pastur *et al.* 2009).

Dataset building and statistical analyses

The dataset was built with a large quantity of data (published and unpublished research) from our two permanent research sites (Appendix A). The primary studies included in this analysis meet the following criteria: (i) the study was carried out in monospecific *N. pumilio* forest; (ii) the forest management was based on VR; (iii) primary unmanaged stands near to harvested areas have been used as a control site; (iv) effects of forest management were assessed by variables related either to forest structure, microenvironment parameters, biodiversity, or forest reproduction; (v) both significant and non-significant results were available, and (vi) raw data and sample sizes were available for each of three treatments: aggregated retention (AR), dispersed retention (DR) and control plots in primary unmanaged forest (PF). We excluded studies that reported effects of natural disturbance and studies that compared different methods of harvesting. In total, 100 different variables from studies carried out between 2002 and 2012 (1st to 9th years after harvesting-YAH) were obtained (Appendix A). In this synthesis, we consider as an individual case any variable that was measured in AR, DR, and PF, and in any particular YAH (from 1 to 9 years, resulting in *n* individual study cases of the same variable, c.f. Appendix A). Variables that were measured in both study sites during the same year were treated as separate cases. As result, 605 different individual cases were used for our analyses (Appendix A).

All variables included here, fall into four broad categories based on the ecological criteria defined for VR (Chen *et al.* 1995, Franklin *et al.* 1997, Gustafsson *et al.* 2012): (i) structural retention strategies, (ii) maintenance of natural processes, (iii) "life boating" species, and (iv) constant supply of sources for forest reestablishment. Following these four criteria we define the following groups for our analyses: (i) forest structure (e.g. basal area, quadratic mean diameter) with 10 variables and 59 cases; (ii) microenvironment variables (e.g. soil temperature) with 11 variables and 30 cases; (iii) biodiversity variables (i.e. measures of diversity and abundance of taxa and guilds) with 54 variables and 341 cases; and (iv) forest reproduction (e.g. seeds and plant regeneration) with 25 variables and 187 cases (c.f. Appendix A).

To synthesize the outcomes from different studies we performed a quantitative research synthesis using meta-analytical techniques, contrasting and combining the data to identify patterns among the forest treatments (Gurevitch and Hedges 1999). For the overall approach, differences for each of the study cases were analyzed with one-way ANOVAs, considering the following comparisons: AR vs. PF, DR vs. PF and DR vs. AR.

To standardize the results from primary research studies, Pearson correlation coefficients (r) were calculated for each study case, based on F-statistics and sample size (n) (Gurevitch and Hedges 1999):

$$[1] \qquad r = \sqrt{\frac{F}{F + df}}$$

where F is the F-statistic extracted from ANOVAs and df is the degree of freedom for each study case.

Then, Fisher' z was used as a measure of the effect size for each study case:

$$[2] \qquad z = \frac{1}{2}\ln\left(\frac{(1+r)}{(1-r)}\right)$$

where r is the Pearson correlation coefficient.

The individual z-values were combined across studies using a mixed-effects model with categorical data, which assumes that differences among variables within a category or group are due to both sampling error and random variation (Leimu and Koricheva 2004, Paillet *et al.* 2010). The bias-corrected 95% bootstrap confidence intervals generated from 4,999 iterations were used to define the significance of the effects of forest management on each group of variables. Multiyear measurements for studies that spanned more than one year were considered each year as separate entries (Jerabkova *et al.* 2011).

To test the importance of different sources of variation in determining the sign and magnitude of the effect sizes, the total heterogeneity of the sample (Q_t) was examined. For categorical data, the total heterogeneity (Q_t) can be partitioned:

$$[3] \qquad Q_t = Q_b + Q_w$$

where Q_b is the variation of the effect size explained by the fixed effects model, and Q_w is the residual error variance not explained by the model.

Thus, Q_b (between-groups variability) is a description of the difference among group cumulative effect sizes. Q_w (within-group variability) is the residual error heterogeneity, which is identified through the summation of the individual within-group heterogeneity values. Q_t, Q_b and Q_w were tested statistically for significance against the χ^2 distribution (Saha *et al.* 2012). The analyses were carried out using MetaWin statistical program version 2.1 (Rosenberg *et al.* 2000).

To visualize the trend of the impact caused by VR on each variable an impact rate was calculated, by dividing the average value of each case in AR and DR to the PF average values

(AR/PF and DR/PF, respectively). Then, response ratios were calculated (Benayas *et al.* 2009) by comparing aggregated [ln(AR/PF)] and dispersed retention [ln(DR/PF)] to primary unmanaged forests for each measured variable. Simple ANOVAs were carried out to examine whether response ratios differed among groups of variables. Negative log response ratios indicated a decrease in the value of the variable according to the VR harvesting impact, while positive values indicated an increase. A post-hoc Tukey test (honestly significant difference) was used. Finally, to evaluate the effect of the time since intervention, the individual cases were grouped into three categories according to YAH: 1–2, 3–4 and 5–9 years. Simple ANOVAs were carried out to examine whether the effect sizes differed among YAH periods for each comparison (AR vs. PF, DR vs. PF and DR vs. AR) and group of variables (forest structure, microenvironment, biodiversity, and forest reproduction). Tukey test was applied when significant differences occurred. The significance level for all analyses in this study was set at $\alpha = 0.05$.

RESULTS

For the overall analysis, the variance explained by the three comparisons (AR vs. PF, DR vs. PF, AR vs. DR) ranged between 41.6% and 61.9% (Table 1). AR vs. PF showed a positive (significant) effect size, as well as DR vs. PF (non-significant), whereas DR vs. AR showed a negative (significant) effect. This means that most of the studied variables in the comparison of AR vs. PF presented an increment in the magnitude of the values. Contrary, DR vs. AR presented a decrease in the magnitude of most of the variables. In DR vs. PF the non-significant overall effect in the comparison was due to outbalancing positive and negative effect sizes. Total heterogeneity (Q_t) was significant in both comparisons that included DR ($pQ_t \leq 0.001$). Within each comparison, significant contrasting responses were detected between groups of variables to retention harvesting (Q_b <0.001 for three comparisons). However, there was low residual variance for the model we used for the three comparisons (Q_w >0.05), indicating high internal homogeneity within groups (Table 1).

For forest structure variables, AR maintained similar values as PF (z = -0.06) and the confidence interval showed a non-significant effect size. In DR the parameters had lower values than in PF (z = -0.83) and AR (z = -0.79) (Fig. 1). This implies that most of the forest structure variables decreased in magnitude in DR but not in AR. For microenvironment variables, the values corresponding to AR (z = -0.02) and DR (z = 0.04) were similar to PF, and the confidence interval showed a non-significant effect size. However, when directly comparing the two forms of variable retention, the effect size was significantly higher in DR than in AR (z = 0.24), showing that most of the microclimatic variables increases in DR. For the group of biodiversity variables, the values were significantly higher in DR (DR vs. PF: z = 0.23; DR vs. AR: z = 0.06), and also in AR when compared with PF (z = 0.19). This implies that the biodiversity variables on average increased in forest stands under variable retention. Finally, the variables related to forest reproduction were highest in AR (AR vs. PF: z = 0.13; DR vs. AR: z = -0.18), while no differences were found for DR vs. PF (Fig. 1). In AR most of the regeneration related values increased compared to PF, mainly related to number of propagules, and in DR vs. AR also due to a gradual availability of light and soil moisture. No differences were found between DR vs. PF, attributable to the fact that some variables increased (e.g. height plant and growth) while others decreased in magnitude (e.g. seed production).

In concordance with the previous results, the mean response ratios AR/PF and DR/PF showed significant differences for forest structure variables (F = 26.88, p <0.001; AR/PF was slightly positive and DR/PF strongly negative) and forest reproduction variables (F = 5.03, p = 0.02; AR/PF was clearly positive and DR/PF clearly negative) (Fig. 2). Microenvironment variables showed very weak effects for AR and DR treatments, while biodiversity variables showed positive values for both ratios, being slightly higher in DR/PF (mean response ratio = 0.256) than in AR/PF (0.228). Mean response ratios were neither significantly different for microenvironment (F = 2.16, p = 0.147), nor for biodiversity (F = 0.07, p = 0.785).

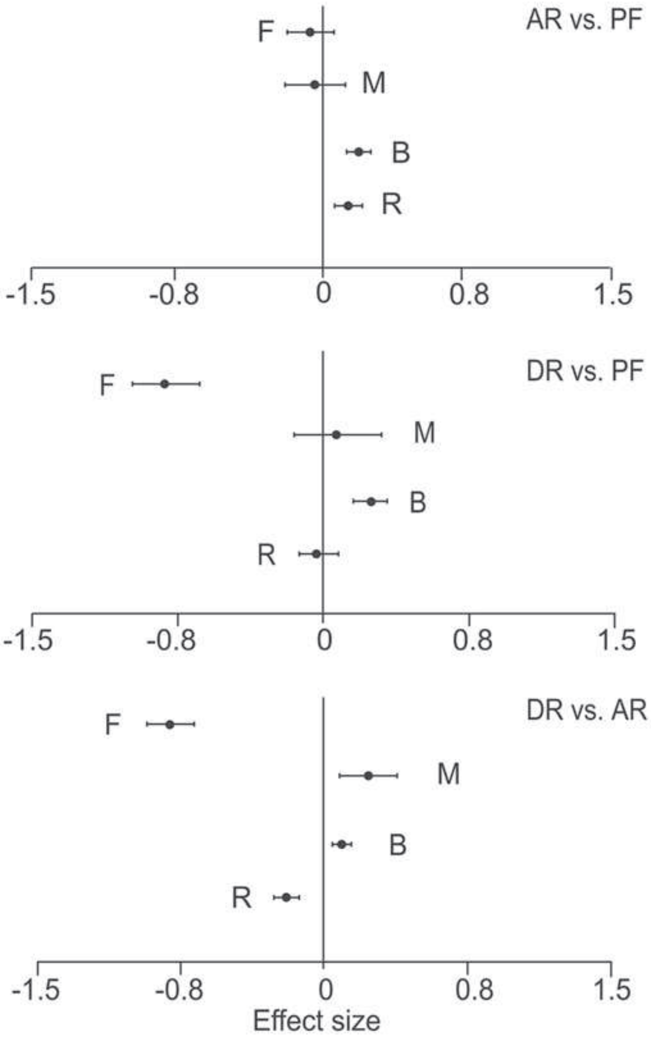
As described before, the impact rate of individual cases included positive and negative values within all four considered groups (Fig. 3). The number of cases with positive

TABLE 1 *Overall effect (d.f. = 602) and disaggregated heterogeneity of effect sizes obtained by meta-analysis of variable retention in Nothofagus pumilio forests, considering four groups of variables (forest structure, microenvironment, biodiversity, forest reproduction) and comparing aggregated retention vs. unmanaged forests (AR vs. PF), dispersed retention vs. unmanaged forests (DR vs. PF), and dispersed vs. aggregated retention (DR vs. AR). Variables used in the meta-analysis are listed in Appendix A*

Comparison	E	CI	Qt	pQt	Var	Qb	pQb	Qw	pQw
AR vs. PF	0.136	0.100 to 0.173	592.5	0.634	43.0	18.3	<0.001	574.2	0.786
DR vs. PF	0.04	–0.021 to 0.095	712.1	0.001	65.9	121.8	<0.001	602.2	0.626
DR vs. AR	–0.08	–0.131 to –0.042	812.9	<0.001	41.6	183.7	<0.001	629.1	0.168

E = effect size; CI = boostraping confidence interval; Qt = total heterogeneity of effect sizes; pQt = probability of total heterogeneity tested against a chi-square distribution; Var = pooled variance explained (%); Qb = between-groups heterogeneity; pQb = probability of between-groups heterogeneity tested against a chi-square; Qw = within-group heterogeneity; pQw = probability of within-group heterogeneity tested against a chi-square distribution.

FIGURE 1 *Effects of variable retention in Nothofagus pumilio forests on forest structure (F), microenvironment (M), biodiversity (B), and forest reproduction (R) variables, for each comparison: aggregated retention vs. primary unmanaged forests (AR vs. PF), dispersed retention vs. primary unmanaged forests (DR vs. PF), and dispersed vs. aggregated retention (DR vs. AR). The effects of treatments are significantly different when 95% confidence intervals do not overlap 0. Variables and their grouping are shown in Appendix A*



impact rate was highest for AR/PF and lowest for DR/AR regarding forest structure, biodiversity, and forest reproduction variables. For microenvironment variables, all three comparisons showed similar numbers of negative impact rates.

The most important temporal trends were increase of the negative impact of DR on forest structure and an increase of the positive impact of both treatments on biodiversity with time (Fig. 4). However, only the effect size for microenvironment variables showed a significant trend, as AR vs. PF and DR vs. PF had positive values for 1–2 and 3–4 YAH, but negative values for 5–9 YAH. For the other groups of variables and comparisons, slight tendencies were observed, e.g. the negative impact of DR on forest structure tended to increase with time as did the positive impact of both treatments on biodiversity (Fig. 4).

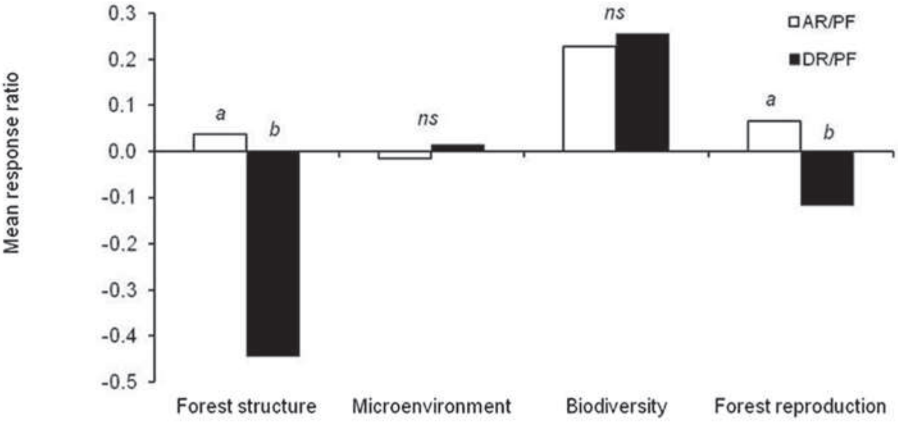
DISCUSSION

Differential response among groups of variables to variable retention

Understanding the effectiveness of retention forestry is one of the critical steps in promoting the integration of wood production and conservation in timber forests (Lindenmayer *et al.* 2012), particularly as the use of this approach is widespread and increasing around the world. Our results indicate that ecological conditions of *N. pumilio* forests are influenced by variable retention management. However, the direction and magnitude of the effect depends on the treatment and differs strongly among groups of variables. As it was expected, harvesting with dispersed retention strongly diminished many of the recorded forest structure variables (e.g. basal area, volume, tree density, canopy cover), while only few of them (e.g. debris cover on the forest floor) being positively influenced by the cuts. In Tierra del Fuego, as in other parts of the world (Attiwill 1994, Gustafsson *et al.* 2010, Scott *et al.* 2012), not only living trees are retained in variable retention management but also other structures, such as treetops, branches, dead wood and stumps of felled trees, which were conserved as legacies. These kinds of structures have been described as key components for the conservation of several biological groups such as insects (Grove and Forster 2010), and to create post-cut habitats resembling natural disturbance regimes such as wind-felled trees (Veblen *et al.* 1996). On the other hand, some variables (e.g. litter fall) for the AR vs. PF comparisons showed positive and negative effects in different study cases of this synthesis. These different responses could be more associated with natural inter-annual variations than with the harvesting impact.

For microenvironment variables, we were unable to detect a significant effect for AR vs. PF and DR vs. PF. The heterogeneity of the measures and the low sample size of cases per variable included in this group is likely an explanation for this result (Osenberg *et al.* 1997). Despite these constraints, our results do suggest that environmental factors within forest aggregates differ from those of scattered retained trees. Canopy openness originated by harvesting changes the microclimatic conditions (e.g. radiation, temperature, rainfall, soil moisture, wind intensity) inside both aggregates and dispersed trees. However, aggregates have buffered microclimatic conditions more similar to undisturbed mature forest. According to Martínez Pastur *et al.* (2011a), when distance from edge of aggregates is considered, solar radiation and soil moisture increased from inside aggregates towards outside sectors (harvested areas). Similar patterns have been reported by Heithecker and Halpern (2007) in Douglas-fir forests in western Washington (USA). In our study, some microenvironment variables were negatively affected inside aggregates

FIGURE 2 *Response ratios of different groups of variables to aggregated (AR/PF) and dispersed (DR/PF) retention standardized with values for the primary unmanaged forest. Letters indicate significant differences between pair comparisons (Tukey test at p < 0.05)*



(e.g. soil moisture) likely because they were inserted in a matrix of harvested area with dispersed retained trees.

The group of biodiversity variables showed the highest quantity of cases with positive effect sizes and the greatest impact rate. This can be explained by increases of α-diversity or cover of native species that have already been present in the original forest before harvesting, and the immigration of other species from neighboring environments (e.g. grasslands) after harvesting. This immigration can be stimulated by a broader range of climatic and environmental conditions (Chen *et al.* 1995, Promis *et al.* 2010), for instance for the foraging and breeding of birds (Lencinas *et al.* 2009). The introduction of alien species (e.g. understorey plants) inside the managed forests after harvesting (Lencinas *et al.* 2009) is an undesirable consequence, because most alien species remain in the understorey of secondary forests (Arnott and Beese 1997, Martínez Pastur *et al.* 2002, Nelson and Halpern 2005) and compete with native species (Moore and Goodall 1977). Similar results were stated by Rosenvald and Lõhmus (2008) and Fedrowitz *et al.* (2014), who reported an increase of biodiversity after green tree retention was applied.

Negative effects of VR on particular biodiversity variables corresponded to a decline of organisms sensitive to harvesting, e.g. bryophytes (Lencinas *et al.* 2008), a pattern that was also observed in other temperate forests (Hazell and Gustafsson 1999, Jalonen and Vanha-Majama 2001, Rosenvald and Lõhmus 2008, Fedrowitz *et al.* 2014). Both an increase and decrease of biodiversity variables implies an ecological impact by VR. The detected increases of adventive species should not be considered as a benefit for biodiversity conservation, because sustainable management aims at conserving the primary forest legacies (Franklin *et al.* 1997; Lindenmayer *et al.* 2012).

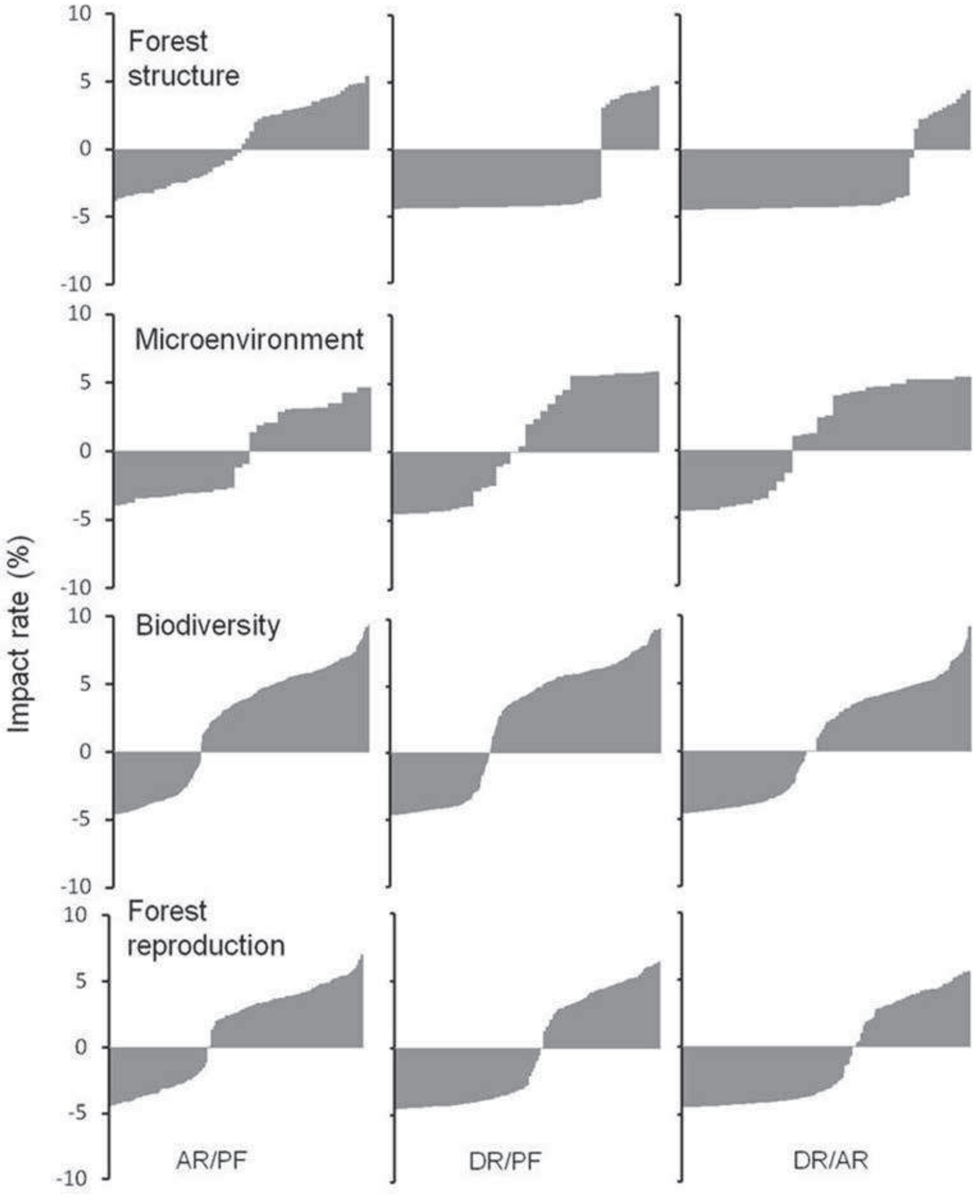
In the forest reproduction group of variables, the positive impact rates were associated with greater natural regeneration recruitment and growth in the harvested forests (Martínez Pastur *et al.* 2011a, 2011b). For instance, Martínez Pastur *et al.* (2008, 2013) have reported a reduction in the proportion of empty seeds compared to PF, thereby increasing the proportional reproductive success (Pulido *et al.* 2010). Likewise, most of the negative impact rates were mainly related to flowers (male and female) and seed biomass. The effects on forest reproduction caused by variable retention indicate good conditions for establishment, growth and development of secondary forests after harvesting, which is one of the main management objectives for the regeneration of silvicultural systems (Daniel *et al.* 1979, Smith 1986).

Temporal trends in the effects of variable retention

Our results for the 1st to 9th YAH under VR in *N. pumilio* forests showed only a few significant differences among the three considered periods. The impacts tended to increase towards the last period for some groups (e.g. microenvironment and biodiversity variables) and to diminish for others (e.g. forest reproduction variables). The significance found in microenvironment variables was determined by few cases related to forest floor characteristics in 5–9 YAH, being negatively affected by harvesting (e.g. bare soil cover). However, other microenvironment variables can show positive and negative changes during the 5–9 YAH, e.g. radiation (Promis *et al.* 2010). Therefore, the result for this period should be complemented with more study cases. Likewise, most analyzed cases for the other groups of variables were originated from the first four YAH, and the robustness of this analysis could be improved with more data in the medium-long term (>5 YAH).

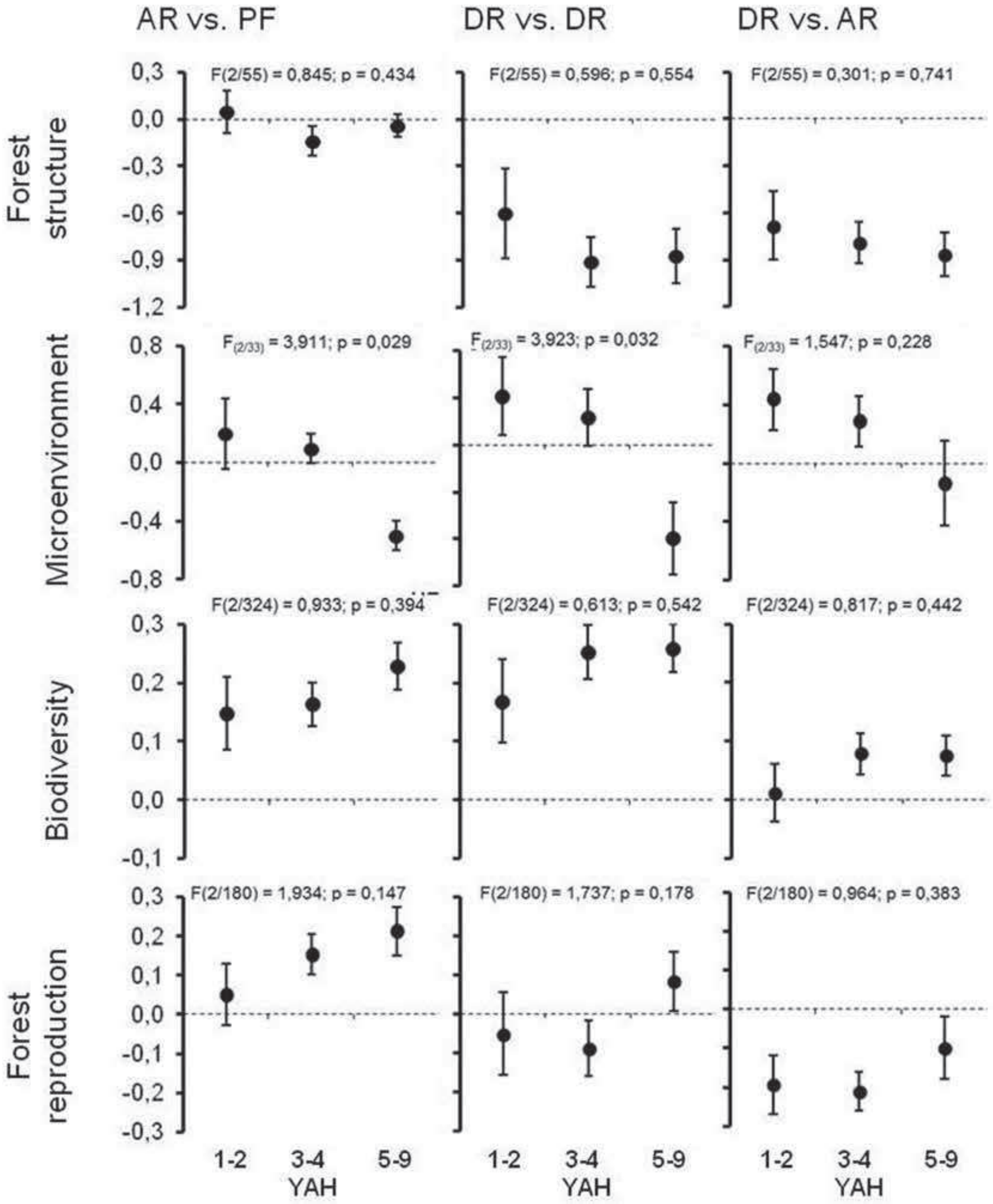
Biodiversity in primary forests adjacent to harvested stands could also be indirectly affected by harvesting, where the stand conditions would not be sufficiently buffered to maintain species sensitive to environmental changes (Heithecker and Halpern 2007, Lencinas *et al.* 2011). Likewise, some variables had a quick response to changes in some environmental conditions, e.g. the relative abundance of insects at canopy level increased 8 times in dispersed retention from 1 to 4 YAH, and the male flower production increased 3 times

FIGURE 3 *Impact rate (%) for each case used in the analysis of variable retention in Nothofagus pumilio forests, specified for the four groups of variables and different comparisons: aggregated retention vs. primary unmanaged forests (AR/PF), dispersed retention vs. primary unmanaged forests (DR/PF), and dispersed vs. aggregated retention (DR/AR)*



in aggregates and dispersed retention from 1 to 3 YAH. Other ecological variables could have a strongly delayed response to harvesting, e.g. bird density did not greatly vary during the first four YAH. Monocot cover, both in AR and DR, slightly increased in the first two YAH, but this change became significant only 8 YAH. Our analysis assessing the temporal effects on biodiversity variables showed that in dispersed retention the plateau was reached faster than for aggregates, and future assessments will show whether the detected biodiversity surplus might be temporal, and whether immigration credit will be completely compensated by extinction debt (Jackson and Sax 2010). The impact of variable retention along the YAH could be better understood if base-line studies are carried out before the harvesting in the same stands (e.g. before-after-control-impact approach) (Underwood 1991, Smith *et al.* 1993). Base-line studies prior to harvesting were not included in our study, but at least two replicates of unmanaged primary forests were used as controls. We consider that monitoring of different control sites is useful to evaluate not only the effect of harvesting impact on ecological variables, but also the spatial variation of the original conditions due to natural variability. Variable retention has only been applied worldwide for a few decades; therefore there are few permanent research sites with more than 20 years of reliable data (Spence *et al.* 2002, Aubry *et al.* 2004, Martínez Pastur *et al.* 2010, Gustafsson *et al.* 2012). There is a strong need to extend

FIGURE 4 *Temporal effects of variable retention impact over environmental variables in Nothofagus pumilio forests. Effect sizes are shown for three different time periods (1–2 years after harvesting-YAH, 3–4 YAH and 5–9 YAH), considering four groups of variables and different comparisons: aggregated retention vs. primary unmanaged forests (AR vs. PF), dispersed retention vs. primary unmanaged forests (DR vs. PF), and dispersed vs. aggregated retention (DR vs. AR). Mean values (black circles), and standard errors (bars) are presented, as well as F-statistic and p value obtained with ANOVAs*



the time-scale of these studies (Fedrowitz *et al.* 2014), particularly to assess if the long-term structural maintenance is effective.

Forest management implications

According to Gustafsson *et al.* (2012), several aims could be achieved with VR harvesting, including ecological, economic, and social ones. In this work we focused on ecological aims, obtaining an overall description of the impacts on *N. pumilio* southern Patagonian forests. Further research should assess economic benefits (Fedrowitz *et al.* 2014) and ecosystem function that contribute to long-term forest services by improving soil-moisture retention, providing nutrient pools and habitat for forest-dwelling species, or preserving the old-growth status of these forests (Lindenmayer 2009). Our study shows that VR has several ecological impacts, but at least in the aggregates, mature forest conditions can be partially maintained. As a consequence, harvested areas that include dispersed and aggregated retention along the entire productive units have a better conservation value than those that only prescribe retention of isolated trees. Individual studies showed that primary *N. pumilio* patches retained as circular aggregates under variable retention are favorable to conserving mature forest associated species and functions (Lencinas *et al.* 2008, 2009, 2011, 2014, Simanonok *et al.* 2011). There is still a lack of knowledge on connectivity issues related to the aggregates and further research on spatial patterns and design of variable retention would be valuable (Rosenvald and Lõhmus 2008). However, this study provides a useful tool for forest managers to enable evidence-based, efficient and sustainable planning, as well as for governmental and civil institutions to generate sustainable forest management policies considering the conservation of biodiversity (Poirazidis *et al.* 2011).

CONCLUSIONS

We conclude that natural ecological conditions of *N. pumilio* forests in Tierra del Fuego are influenced by VR management, but at least some primary forest conditions can partly be maintained inside aggregates. As we expected, the revealed response to variable retention management differed strongly among the groups of variables. Forest structure and biodiversity were the most affected groups. The first case evidences the structural impact produced by timber extraction such as the consequent reduction of canopy cover and basal area. In the second case, a positive effect size can be explained by increases of native species already present in the original forest before harvesting and by immigration of native and exotic species from neighboring environments (e.g. grasslands) after harvesting. Further studies must consider the separated effects of native vs. adventive species for the different groups (plants, birds, and insects). Forest reproduction was positively affected due to greater natural regeneration recruitment and growth, while microenvironment factors were affected marginally.

This synthesis applied all available data to generate results and global conclusions, and allowed visualizing overall effects based on particular findings. Long-term monitoring programs in temperate forests are the only way to understand long-term management effects and contribute thus to sustainable forest management and policy decisions by challenging our understanding of forest attributes and dynamics. In the future, regional peculiarities should also be considered in outlining the conservation objectives (e.g. target taxa) to choose the most appropriate silvicultural treatment.

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APPENDIX A *List of variables of variable retention in Nothofagus pumilio forests, grouped in four categories: forest structure, microenvironment, biodiversity, and forest reproduction. Table shows the number of cases specified by periods of years after harvesting (YAH): 1–2, 3–4, and 5–9 years*

Type	**Name of variable**	**Units**	**YAH**		
			1–2	**3–4**	**5–9**
Forest Structure	Basal area (2)	m^2/ha	1	3	4
	Hemispherical photography cover (3)	%	1	2	
	Canopy cover (6)	%		2	1
	Debris cover (5)	%	3	4	4
	Leaf area index (3)		1	2	
	Litter-fall (1)	ton/ha	3	6	9
	Overstorey	%	1	2	4
	Quadratic mean diameter (2)	cm	1	1	
	Total over bark volume (2)	m^3/ha	1	1	
	Tree density (2)	n/ha	1	1	
Micro-environment	Air humidity	%	1		
	Average air temperature	ºC	1		
	Diffuse radiation (3)	W/m	1	2	
	Direct radiation (3)	W/m	1	2	
	Maximum air temperature	ºC	1		
	Minimum air temperature	ºC	1		
	Soil cover (5)	%	3	4	4
	Soil moisture (0–20 cm)	%		1	
	Soil moisture (20–40 cm)	%		1	
	Soil temperatura	ºC	1		
	Water soil content	%		2	4
Biodiversity	Bird density (4)	ind/ha	2	2	
	Bird richness (4)	sp/plot	2	2	
	Cespitose grass cover (5)	%	2	2	
	Dicot biomass (5)	gr/m	2	2	
	Dicot cover (5)	%	3	4	4
	Dicot richness (5)	sp/plot	3	4	4
	Erect herbs cover (5)	%	2	2	
	Exotic plant cover	%	1	2	4
	Exotic plant richness (5)	sp/plot	3	4	4
	Female flowers foraged by insects (6)	mill/ha	1	2	
	Fern biomass * (5)	gr/m	2	2	
	Fern cover * (5)	%	3	4	4
	Fern richness (5)	sp/plot	3	4	4
	Immature fruit foraged by birds (6)	mill/ha	1	2	
	Immature fruit foraged by insects (6)	mill/ha	1	2	
	Insect abundance at canopy level	ind/set	2	2	
	Insect abundance at soil level	ind/set	2	2	
	Insect abundance at understorey level	ind/set	2	2	
	Insect relative abundance	ind/set	2	2	
	Insect richness	sp/set	2	2	
	Insect richness at canopy level	sp/set	2	2	
	Insect richness at soil level	sp/set	2	2	
	Insect richness at understorey level	sp/set	2	2	
	Lichen cover	%	1	2	4
	Monocot biomass (5)	gr/m	2	2	
	Monocot cover (5)	%	3	4	4
	Monocot richness (5)	sp/plot	3	4	4
	Mosses biomass (5)	gr/m	2	2	
	Mosses cover (5)	%	3	4	4
	Native plant cover	%	1	2	4
	Native plant richness (5)	sp/plot	3	4	4
	Prostrate herbs cover (5)	%	2	2	

Type	**Name of variable**	**Units**	**YAH**		
			1–2	**3–4**	**5–9**
	Rhizomatous grass cover (5)	%	2	2	
	Seeds foraged by birds (1)	mill/ha		3	6
	Seeds foraged by insects (1)	mill/ha		3	6
	Shrub cover * (5)	%	2	2	
	Acaena magellanica cover	%	1	2	4
	A. ovalifolia cover	%	1	2	4
	Blechnum penna-marina cover	%	1	2	4
	Bromus unioloides cover *	%	1	2	4
	Cerastium fontanum cover	%	1	2	4
	Cotula scariosa cover	%	1	2	4
	Dysopsis glechomoides cover	%	1	2	4
	Festuca magellanica cover	%	1	2	4
	Galium aparine cover	%	1	2	4
	Misodendron sp. Biomass (7)	%	1	2	
	Osmorhiza depauperata cover	%	1	2	4
	Phleum alpinum cover	%	1	2	4
	Poa pratensis cover	%	1	2	4
	Rumex acetosella cover	%	1	2	4
	Stellaria media cover	%	1	2	4
	Taraxacum officinale cover	%	1	2	4
	Uncinia lechleriana cover	%	1	2	4
	Usnea sp. biomass (7)	%	1	2	
Forest Reproduction	Aborted seeds (6)	%	1	2	
	Abscised female flowers (6)	%	1	2	
	Abscised immature fruits (6)	%	1	2	
	Dead seeds (6)	%	1	2	
	Empty seeds (6)	%	1	2	
	Female flower biomass (6)	kg/ha	1	2	
	Female flower production (6)	mill/ha	1	2	
	Immature fruit biomass (6)	kg/ha	1	2	
	Immature fruits production (6)	mill/ha	1	2	
	Male flower biomass (6)	kg/ha	1	2	
	Male flower production (6)	mill/ha	1	2	
	Non-viable seeds (6)	%	1	2	
	Regeneration age (1)	Year	5	6	6
	Regeneration biomass (5)	gr/m	2	2	
	Regeneration cover (5)	%	3	4	4
	Regeneration density (1)	thousand/kg	5	6	6
	Regeneration growth (1)	cm/year	5	6	6
	Regeneration height (1)	cm	5	6	6
	Seed biomass (1)	kg/ha	6	10	11
	Seed length (6)	cm	1	2	
	Seed production (1)	mill/ha	5	4	5
	Seed width (6)	cm	1	2	
	Sound seed production (1)	%		3	6
	Quantity of seeds per kg	thousand/kg	2	2	5
	Viable seeds (6)	%	1	2	

* These variables do not have data for all treatments due to low occurrence frequency in samplings during some years after harvesting. Cases of these variables only were used when data exist for the two treatments of each comparison in each year after harvesting. Data source: (1) Martínez Pastur *et al.* (2008); (2) Martínez Pastur *et al.* (2011a); (3) Martínez Pastur *et al.* (2011b); (4) Lencinas *et al.* (2009); (5) Lencinas *et al.* (2011); (6) Martínez Pastur *et al.* (2013); (7) Soler *et al.* (2014). Variables without super-index corresponded to unpublished data.