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Relationships among livestock, structure, and regeneration in Chilean Austral Macrozone temperate forests

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ABSTRACT

A Macrozone is a socioecological region with shared geographic and demographic characteristics. Within the Chilean Austral Macrozone (43° to 56° SL), the native temperate forests serve as a crucial resource, offering multiple ecosystem services to local communities. These forests significantly support animal husbandry practices involving cattle, horses and sheep. However, introducing these exotic species affects natural regeneration and compromises their long-term sustainability. This study proposes a new classification of the temperate forests in the Chilean Austral Macrozone based on structure parameters and determine their relationships with animal husbandry and natural regeneration. Data were obtained from Chile's National Forest Inventory (NFI) (2001–2010), including 195 inventory plots (500 m^2) with 21 tree species. We redefined the forest categories described in NFI according to the proportional basal area of each tree species at each plot. We used two levels of analysis: forest composition (Level 1), which includes general categories such as mono-specific (dominated by a single tree species), bi-specific (dominated by two tree species), and multi-specific forests (dominated by multiple tree species), and forest type (Level 2), which includes specific species (e.g., *Nothofagus pumilio*) or species groups (e.g., *N. pumilio* - *N. dombeyi*) with economic relevance. We evaluated the data using univariate and multivariate analyses. We found 18 forest types in the Austral Macrozone, in contrast to the three traditionally recognized forest types used in the NFI (e.g., lenga, evergreen, coihue de Magallanes). Livestock was observed in all forest types, where *Nothofagus* forests showed that regeneration in *N. antarctica* and *N. pumilio* were higher with livestock than without livestock breeding (Hedges' $g > 0.51$). The natural regeneration of the studied forests was influenced by animal husbandry, environmental variables (bioclimatic and topographic factors), and forest structure. Our data suggested the importance of using more forest types than the three classics to generate tools or recommendations that are more focused on the particularities of each one. The classification must be based on forest parameters obtained during NFI. The proposed forest type classification reflects the complexity and richness of the forests in a better way, which could improve forest management and the development of public policies related to climate change and sustainability. Finally, although livestock pressure was observed in all forest types, the impact over some areas (e.g., *N. antarctica*) needs special attention in the forest management and conservation planning for the Chilean Austral Macrozone.

1. Introduction

Native forests are essentially natural and socioecological resources (Chhatre and Agrawal, 2008; Huertas Herrera et al., 2023). They provide multiple ecosystem services to local inhabitants, such as recreation, biodiversity conservation, soil, and water quality (Martínez Pastur et al., 2020a; Orsi et al., 2020; Peri et al., 2021). In forests used for animal husbandry, grazing disrupts the continuity of native forests by exceeding degradation thresholds that affect, among other things, the natural regeneration of trees (Salinas et al., 2017a; Rusch and Varela, 2019). Natural regeneration is one of the main ecological processes through which stands recover (Toro Manríquez et al., 2019, 2023) in response to

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natural or anthropogenic disturbances, such as animal husbandry (Martínez Pastur et al., 2013; Peri et al., 2016, 2017; Chillo et al., 2021). Natural regeneration indicates the potential composition and quality of future forest stands, encompassing species diversity, structural complexity, and overall ecosystem functionality (Gilliam, 2007; Martínez Pastur et al., 2020b).

In forest ecosystems, livestock can be a risk to natural regeneration, posing challenges to the long-term sustainability of forests (Salinas et al., 2017b; Quinteros et al., 2017; Öllerer et al., 2019). In previous studies, extensive livestock trampling has been observed to induce changes in the soil's physical structure and alter plant composition (Quinteros et al., 2010; Török et al., 2014; Rhodes et al., 2018). For instance, competition with other plant species, including understory vegetation, can be intensified as livestock consume or trample the natural regeneration, affecting their chances of survival and growth (Beckage et al., 2000; Gilliam, 2007; Martínez Pastur et al., 2022), as well as energy and nutrient cycling (O'Brien et al., 2007; Peri et al., 2017). These cumulative effects modify the natural dynamics of the forests (Peri et al., 2016; Mazzini et al., 2018), highlighting the importance of understanding and mitigating the impacts of animal husbandry in forest ecosystems.

Therefore, any forest management proposal under animal husbandry involves reconciling production with conservation by incorporating conservation components into productive environments (Lindenmayer et al., 2006, 2012). This perspective is necessary to address, for example, the growing international demand for forest and animal products (Fischer et al., 2009; Havlík et al., 2014; UNDP, 2020), considering the need to implement management practices that promote tree regeneration (Chhatre and Agrawal, 2008; Aryal et al., 2022). For long-lived tree species, the early stages of the establishment (e.g., germination and survival) are more vulnerable to extreme temperatures and precipitation (Fenner and Thompson, 2005; Pissolito et al., 2021), which is crucial in the long term for seed germination requirements and survival rates (Walck et al., 2011; Kołodziejek et al., 2017). Considering the above, climatic events influence forest regeneration and should be considered in forest planning and management (Millar et al., 2007; Toro Manríquez et al., 2023). Many topics of natural dynamics (e.g., seed production and regeneration) in primary and managed forests (pure and mixed forests) have been studied (Martínez Pastur et al., 2014; Arpigiani et al., 2022). In addition, seed production and seedling recruitment were correlated with regional climate, where temperature and precipitation were the main explanatory factors (Torres et al., 2015; Toro Manríquez et al., 2023).

In this context, National Forest Inventories (NFI) are sources of information widely used in decision-making for native forests at a regional scale (Álvarez-González et al., 2014; Jevšenak and Skudnik, 2021). In Chile, NFI was conducted by the Forest Institute (INFOR) and provides information on the different forest categories, including forest structure, biometry, socio-ecology, and livestock breeding (Bahamondez et al., 2016). However, the used forest categories are based on old phytosociological descriptions (Donoso 1981). Although this forest categorization is supported by the national legislation (Law 20,283 of Native Forest Recovery and Forest Promotion), it masks some essential differences among forests, as the more appropriate conditions in some of them for specific productive activities, such as animal husbandry in *Nothofagus antarctica* forests or timber extraction in *N. pumilio* forests. Considering this, a comprehensive examination of the existing forest types based on broader criteria, such as biometric analysis (e.g., basal area) of all the tree species, becomes imperative.

The objective of this study was to propose a new classification of the temperate forests in the Chilean Austral Macrozone based on structure parameters and determine their relationships with animal husbandry and natural regeneration. To this end, the following specific objectives were raised: (i) Evaluate whether forest types are differentially used for animal husbandry (cattle, horses, and sheep) and identify the most utilized forest structures, considering bioclimatic and topographic factors, and forest structure. (ii) Assess how the natural regeneration of these forests varies concerning forest types, animal husbandry, and other variables that may affect it. The resulting information could provide insight to improve regional management and conservation planning.

2. Methods

2.1. Study area

We focus our study on the Chilean Austral Macrozone. It is an extensive socioecological region, covering approximately 250,000 km^2, with comparable geographical and demographic features, spanning about 1500 km on its mainland (from north to south). The Chilean Austral Macrozone (Fig. 1) comprises the regions of Aysén (108,494 km^2) and Magallanes (132,291 km^2). The Chilean Ministry of Science, Technology, Knowledge, and Innovation through its Regional Ministry Secretary (SEREMI), designated the Chilean Austral Macrozone in 2019 (decree N° 7 of the Ministry of CTIC). This aimed to promote a center of scientific knowledge for sustainable development in the southernmost region of the world and improve, among other things, nature conservation and quality of life for its inhabitants. One of the main economic activities in the Chilean Austral Macrozone is the animal husbandry, which is part of the cultural identity of the local population (Schmidt, 2013; Salinas et al., 2017a; GORE, 2021). Traditionally, natural grasslands have been used for animal forage (Salinas et al., 2017b). However, in recent years, the intensity of their use has led to a decline in their productive capacity (Salinas, 2017; Chillo et al., 2021), resulting in the introduction of livestock into previously marginal areas, such as native forests (Fig. 2). Cattle (*Bos taurus*), horses (*Equus caballus*), and sheep (*Ovis aries*), among others, are raised in these areas as they provide an alternative for the livestock's needs (e.g., forage, animal comfort, shelter during long winters).

2.2. Data source

The data was obtained from the National Forest Inventory (NFI) of INFOR (see details at https://www.infor.cl), complying with the Biophysical Data Transfer Protocol (Bahamondez et al., 2021). These data corresponded to the first cycle of NFI conducted between 2001 and 2010 (Copyright © 2022 NFI INFOR). The experimental design included a systematic sampling, with a bi-stage statistical design of clusters distributed in a 5 × 7 km grid, covering the whole Chilean forest landscape. These clusters consisted of three concentric circular plots with equivalent areas of 500 m^2 to measure forest structure and three subplots of 1 m^2 to measure tree species and natural regeneration. The inventory information is presented in data matrices that provide: (i) qualitative information about the clusters (e.g., ID, forest category), plots and subplots (e.g., ID, slope, drainage, exposure, relief), (ii) forest structure and composition (e.g., species, diameter at breast height - DBH, stump, total height, bark thickness), and natural regeneration (e.g., species, stratum, frequency), and (iii) livestock presence (e.g., cattle, horses, sheep) in the clusters. Supplementary Table S1 shows the used data type from the NFI of INFOR.

In the NFI, plants higher than 1.3 m and with a basal diameter at breast height (DBH) less than 4.0 cm were considered natural regeneration. Their frequency was surveyed. We expressed the quantity in hundreds of thousandth in tables and figures. For example, 2.6 = 260,000 plants.

For the bioclimatic characterization of each plot, NIF information was complemented with geographic location (latitude and longitude), elevation (m a.s.l.), mean annual temperature (°C) and precipitation (mm year^{-1}) (these last two obtained from WorldClim 2 database; Fick and Hijmans, 2017).

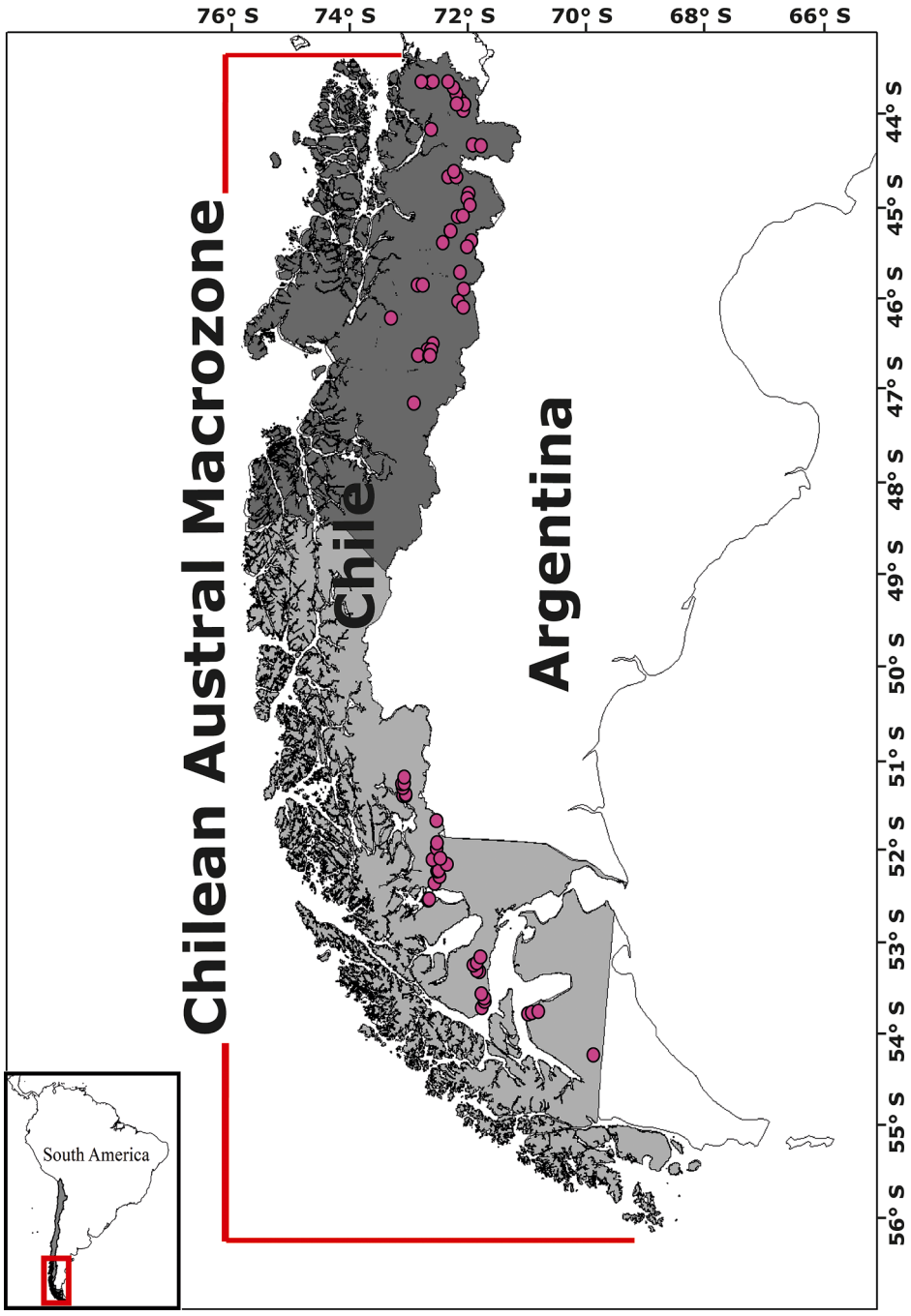

Fig. 1. Study area in the Chilean Austral Macrozone: Aysén (dark grey) and Magallanes (light grey) regions. The purple dots indicate the clusters studied in the INFOR National Forest Inventory (NFI).

2.3. Rationale of the study

The NFI recognizes three forest categories ("lenga," evergreen, and "coihue de Magallanes") for the Chilean Austral Macrozone. This categorization is based on a traditional description of the native forests, as documented by Donoso (1981) and Papageorgiou and Massai (2020). As was stated before, this traditional approach hinders some characteristics of the tree species and forests. For example, productive activities like animal husbandry usually occur in *Nothofagus antarctica* (ñire) forests, while timber activities are conducted in *N. pumilio* (lenga) forests. Ñire forests exhibit a distinct structure and composition (Salinas et al., 2017a, b), often appearing as mono-specific stands (Schmidt, 2013; Salinas, 2017). However, it was included as a component of the lenga forest category in the NFI (Donoso, 1981; Sotomayor, 2016).

Based on forest structure and composition data, we redefined the three forest categories described in the NFI according to classification parameters derived from the proportional basal area (BA) of each forest species (Fig. 3A). The analysis of these parameters was conducted for each plot within each cluster, considering two different levels of analysis: forest composition (Level 1) and dominant species (Level 2). The Level 1 analysis was conceived as follows: (i) when one single species was necessary to reach ≥70% BA, it is a mono-specific forest; (ii) when two species were necessary to reach ≥70% BA, it is a bi-specific forest, and (iii) when more than two species were necessary to reach ≥70% BA, it is a multi-specific forest. For Level 2 analysis, we focused on the dominant species to define the forest types. For this, we used a standard

Fig. 2. Animal husbandry in *Nothofagus* forests, with *N. pumilio* (lenga) depicted in the upper and *N. antarctica* (ñire) in the lower figure.

abbreviation of the scientific name (the genus' first two letters and the species' initial two letters into a single uppercase word), which intuitively facilitates the interpretation of the tree species involved in the proposed forest types of Level 1 (Fig. 3B). For multi-specific forests with three or more species, the abbreviation was MULTI. Fig. 4 shows the new proposed forest types, including the partial results of the two stages (Level 1 and Level 2) of the analysis.

Animal husbandry was analyzed and classified into the following categories (Fig. 3C): (i) Non-livestock when no presence of livestock was reported in the plot; (ii) Cattle when only the presence of cattle was reported in the plot; (iii) Cattle-horse when the presence of horses was reported, alone or in a combination of cattle; (iv) Sheep-other when the presence of sheep was reported in combination with other types of livestock. The reason for classifying sheep in the Sheep-other category is that they were consistently reported in conjunction with other types of livestock, such as sheep + cattle, sheep + horses, or sheep + cattle + horses. It is important to note that although there were instances where other types of livestock (e.g., goats) were present in certain plots, these were excluded from the study due to their low representation. The intensity of animal husbandry was determined by the frequency of reported livestock presence (e.g., the number of times that different livestock types were reported at each plot). The intensity levels were categorized as follows: Low (1 or 2 reports of livestock presence), Middle (3 or 4 reports of livestock presence), and High (>5 reports of livestock presence). The analysed data matrices of the NFI had unique identifiers for each cluster ($n = 95$), allowing us to correlate the animal husbandry information with the redefined forest categories (Fig. 4) and natural regeneration (e.g., quantity of plants). Please refer to Figure S1 for a visual representation of the process used to concatenate the forest inventory matrices.

2.4. Data analyses

For the analyses, the average of plots for each cluster was used as a replica. To assess heterogeneity in the regeneration composition at Level 1, we performed a Detrended Correspondence Analysis (DCA).

We evaluated animal husbandry through Generalized Linear Models (GLM) to assess regeneration loss, evaluating the effect of livestock presence, intensity, and natural regeneration occurrence. Due to the number of replicas for each category, we reclassify Level 2 to address the imbalance of treatments (see Table S2). This reclassification created a category called OTHER, which encompassed mono- (e.g., NOAN), bi- (e.g., NODO-DRWI), and multi-specific (e.g., MULTI) forest types, which presented a lower number of plots. Thus, the reclassified Level 2

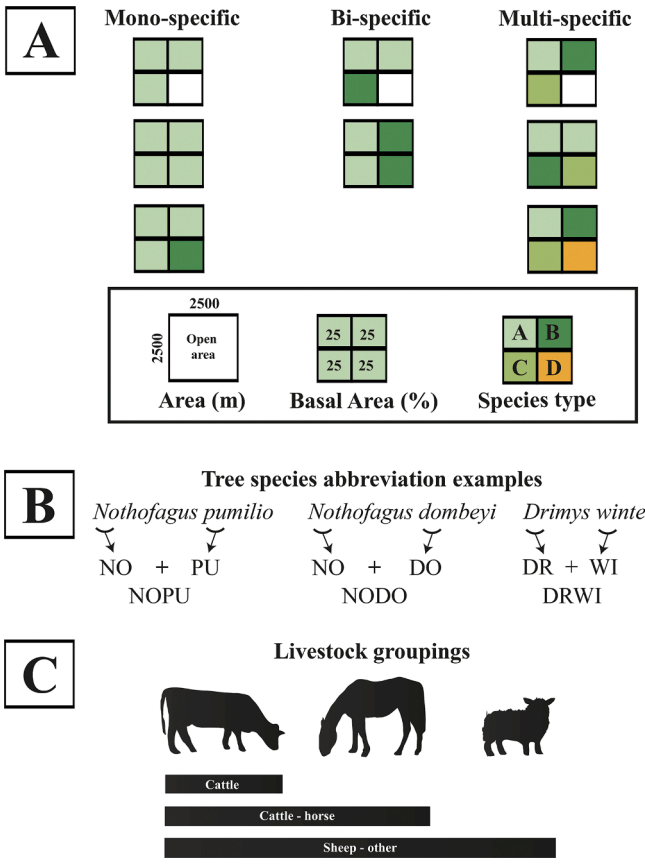

Fig. 3. Data analysis framework.

includes the following treatments: NOAN (*N. antarctica*), NOPU (*N. pumilio*), and OTHER (other deciduous or evergreen categories). The GLMs were conducted using a Poisson distribution, but since the regeneration counts were highly dispersed, a negative binomial distribution with a logarithmic link function was applied. The following predictor variables were tested as categorical variables: (i) Livestock presence (non-livestock, cattle, cattle-horse, sheep-other), (ii) Livestock pressure (non-livestock, low, middle, high), (iii) Level 1 (mono-, bi-, multi-specific), and (iv) Level 2 (NOPU, NOAN, OTHER). The cluster effect was analyzed using the lower Akaike Information Criterion - AIC value. Mean comparisons were conducted using Fisher's Least Significant Difference (LSD) test ($p < 0.05$). We used the InfoStat software to perform these analyses (Di Rienzo et al., 2018).

Based on the results of GLM, we focused on Level 2 (i.e., NOAN, NOPU, OTHER) for the following analyses. We used a chord diagram in R-Studio (www.rstudio.com), created with the Circlize library version 0.4.13 (Gu et al., 2014), to visualize the relationship between natural regeneration and livestock type and pressure. Additionally, we used a Principal Component Analysis (PCA) to examine the relationship between natural regeneration and environmental variables, livestock presence, and forest structure (e.g., DBH, total height) for Level 2 as an indicator variable (dummy variable). These statistical analyses were performed using PC-Ord (McCune and Mefford, 1999). From the PCA results, we evaluated the effect size of the amount of area occupied by trees (e.g., total basal area) and the presence of livestock (non-livestock vs. livestock) on the natural regeneration of forest types using Hedges' *g* coefficient (Hedges and Olkin, 1985). The Hedges' *g* is an inferential measure used to calculate effect size (small, medium, and large effects), particularly in cases where sample sizes differ. It measures the difference between groups, often experimental and control groups. For this analysis, we considered the basal area per cluster as a measure of tree density, where a basal area <30 m^2 was considered low, 30–50 m^2 was moderate, and >50 m^2 was considered high.

3. Results

Our final database comprised 95 clusters (Aysén = 40, Magallanes = 55), where 4594 trees belonging to 195 forest inventory plots (500 m^2 each) were analyzed. This database included 21 different tree species representing various families: Asteraceae (*Dasyphyllum diacanthoides*), Atherospermataceae (*Laurelia sempervirens*), Celastraceae (*Maytenus magellanica*), Elaeocarpaceae (*Aristotelia chilensis*), Cunoniaceae (*Caldcluvia paniculate, Weinmannia trichosperma*), Cupressaceae (*Pilgerodendron uviferum*), Monimiaceae (*Laurelia philippiana*), Myrtaceae

Level 1	Level 2	Species involved
Mono-specific forest	NOAN	*Nothofagus antarctica*
	NODO	*N. dombeyi*
	NOPU	*N. pumilio*
	LOHI	*Lomatia hirsuta*
	SACO	*Saxegothaea conspicua*
Bis-pecific forest	NOPU-NODO	*N. pumilio* - *N. dombeyi*
	NODO-NOAN	*N. dombeyi* - *N. antarctica*
	NODO-DRWI	*N. dombeyi* - *Drymis winteri*
	NODO-EMCO	*N. dombeyi* - *Embothrium coccineum*
	NODO-LOHI	*N. dombeyi* – *L. hirsuta*
	NODO-NONI	*N. dombeyi* - *N. nitida*
	NODO-SACO	*N. dombeyi* - *S. conspicua*
	NODO-WETR	*N. dombeyi* - *Weinmannia trichosperma*
	LAPH-AMLU	*Laurelia philippiana* - *Amomyrtus luma*
	LAPH-NODO	*L. philippiana* - *N. dombeyi*
	LAPH-SACO	*L. philippiana* - *S. conspicua*
Multi-specific forest	MULTI	≥3 deciduous and/or evergreen spp. (e.g. *N. dombeyi* - *Drymis winteri* - *E. coccineum*)

Fig. 4. Proposed forest types were identified according to forest composition (Level 1) and dominant species (Level 2) analyses. Fig. 3 provides corresponding color indications for the squares.

(*Amomyrtus luma, Luma apiculata*), Nothofagaceae (*Nothofagus antarctica, N. pumilio, N. betuloides, N. dombeyi*), Podocarpaceae (*Saxegothaea conspicua*), Podocarpaceae (*Podocarpus nubigenus*), Proteaceae (*Embothrium coccineum, Lomatia ferruginea, Lomatia hirsuta*), Rutaceae (*Pitavia punctata*), and Winteraceae (*Drimys winteri*). Some of these species exhibit outstanding values in DBH and dominant height, such as the evergreen L. *philippiana*, which averages 45.9 ± 23.4 cm DBH and 25.9 ± 7.7 m height. Among the species of the *Nothofagus* genus, the evergreen species *N. dombeyi* (34.5 ± 22.3 cm DBH, 19.6 ± 10.7 m height) and the deciduous species *N. pumilio* (32.1 ± 18.9 cm DBH, 13.6 ± 6.2 m height) and *N. antarctica* (20.5 ± 11.0 cm DBH, 7.3 ± 3.7 m height) exhibit differences among them in terms of DBH and height.

The most representative species that presented the highest values (mean ± standard error) of the basal area (m^2 ha^{-1}) were the deciduous *N. pumilio* (80.0 ± 6.5 m^2 ha^{-1}), the evergreens L. *philippiana* (54.9 ± 12.5 m^2 ha^{-1}), *S. conspicua* (53.7 ± 14.3 m^2 ha^{-1}), and *N. dombeyi* (43.8 ± 8.0 m^2 ha^{-1}), and the deciduous *N. antarctica* (23.4 ± 3.0 m^2 ha^{-1}). Considering Level 1, mono-specific forests represent 77.4% (151 plots) of the NFI, followed by bi-specific forests with 15.4% (30 plots) and multi-specific forests with 7.2% (14 plots). The regeneration patterns of Level 1 classification were conducted through a DCA (eigenvalues of 0.2789 for Axis 1 and 0.0561 for Axis 2, and total inertia = 0.5366) that showed different regeneration assembles according to the forest composition (mono- vs. bi- vs. multi-specific) (see Fig. 5). Considering the deciduous species, NOAN regeneration was related to mono-specific forests, while NOPU regeneration was shared between mono- and multi-specific forests. The natural regeneration of evergreen species was mainly associated with multi- and bi-specific forests, where *D. winteri* (DRWI) and *L. philippiana* (LAPH) occupied the center of the DCA triangle.

The analysis of Level 2 allowed us to identify 18 different forest types for the Austral Macrozone (Fig. 6). Most of the forest types ($n = 11$) were concentrated between latitudes 43° to 47°SL, decreasing to the south (48° to 55° SL, $n = 7$). At a regional scale, forest types belonging to the *Nothofagus* genus (NOAN, NODO, NOPU) presented their centroids towards the south (starting from ± 49°S), mainly associated with the lower precipitations (500 to 1000 mm yr^{-1}) and temperatures (5 to 8 °C) in the forested lands of the region. Forest types included the other species (e.g., LAPH, SACO, EMCO) presented the centroids in the north (±44°S), associated with higher precipitations (>1000 mm yr^{-1}) and temperatures (>8 °C). Elevation was another influencing factor, where the greatest diversity of forest types was observed at lower elevations (0 to 300 m a.s.l.).

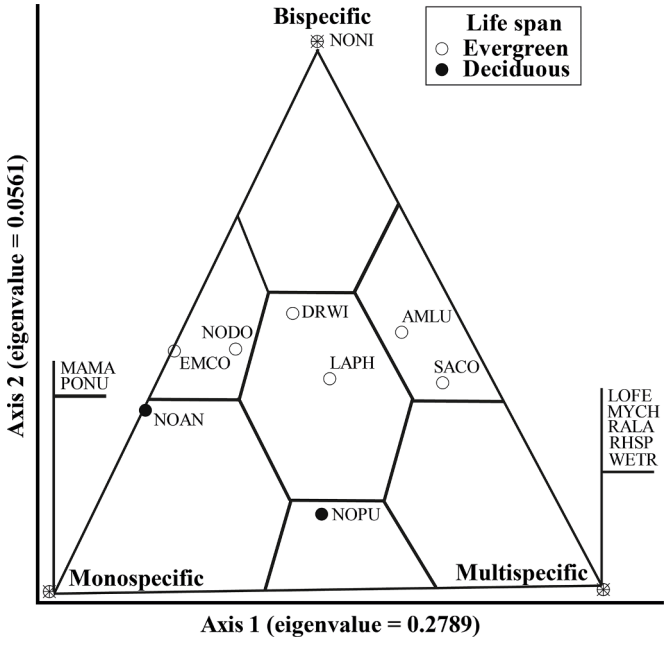

Fig. 5. Detrended Correspondence Analysis (DCA) showing natural regeneration assemblage at mono-specific, bispecific, and multi-specific forest composition levels. The species codes are presented in Fig. 4.

When analyzing the livestock variables with the Level 1 classification, we found that animal use occurred in all of them (Table S2). However, at Level 2, we found some dissimilarities. Forest types with *Nothofagus* species had a higher occurrence of livestock, while evergreen forest types with other species presented a lower occurrence, mainly with one livestock type (e.g., cattle). GLM showed that the effect of livestock presence and pressure on natural regeneration was different among the forest types. AIC values (Tables 1 and 2) showed that the combination of livestock variables (presence type and pressure), and Level 1 and 2 categories explained the natural regeneration of the studied forests (lower AIC value = 1098.65). Natural regeneration was significant and positive for NOPU, with higher natural regeneration than the other forest types (NOAN and OTHER). Besides, livestock presence type was significant and negative with the natural regeneration, where the Sheep-other category indicated lower regeneration values than other livestock types.

Fig. 7 shows the relationships among natural regeneration at different forest types and livestock levels (presence and pressure). The natural regeneration at NOAN, NOPU, and OTHER forest types varied depending on livestock types, where lower regeneration was observed with Sheep-other type as was observed in the GLMs (see Table 1). These effects differed between the forest types. In OTHER category, the presence of livestock consistently showed lower natural regeneration compared to the no-livestock category. On the contrary, when we compared cattle-horse with the no-livestock category, NOAN, and NOPU showed a positive effect over regeneration. Moreover, NOPU regeneration with cattle was similar to the plots without livestock. Besides, these effects were influenced by higher livestock pressure at each forest type, e.g., some plots with higher livestock presence (>5 livestock type presence) tend to present lower levels of natural regeneration.

PCA highlighted the effect of animal husbandry pressure, environmental variables (bioclimatic and topographic) and forest structure on the natural regeneration of the different forest types, showing dissimilar relationships with the studied variables (Fig. 8, Table S3). The first two axes explained 69.9% and 79.9% of the total variation. Axis 1 (eigenvalue = 0.699) was related to the natural regeneration of NOAN and OTHER forest types. For NOAN, a significant correlation was observed between natural regeneration and livestock pressure, indicating that higher levels of regeneration were associated with lower values of forest structure (e.g., less basal area resulted in more NOAN regeneration). In OTHER forest type, the natural regeneration showed a clear association with the bioclimatic variables AMT (annual mean temperature), AP (annual precipitation), and MTDQ (mean temperature of the driest quarter). Besides, lower ISO (isothermality) and higher values of forest structure variables were positively correlated with natural regeneration, especially for NODO within the OTHER forest type category. Axis 2 (eigenvalue = 0.100) explained the natural regeneration of the NOPU forest type, where the higher regeneration was associated with the height of the trees and MTWQ (mean temperature of the wettest quarter). Besides, we found a similar pattern for OTHER forest type, where higher natural regeneration of NOPU correlated with higher forest structure values.

The Hedges' *g* analyses indicated that the effect size of the basal area (low, medium, high) and livestock (non-livestock vs. livestock) over the natural regeneration (NOAN, NOPU, OTHER) presented significant differences (Table 3). When the basal area was high or medium, the effect of animal husbandry over natural regeneration was minimum (Hedges' $g < 0.22$) except for OTHER, where the impact of non-livestock vs. livestock was significant when the basal area was also high (Hedges' $g = 0.63$). In contrast, when the basal area was low, the regeneration of NOAN and NOPU was higher with livestock than without livestock. The

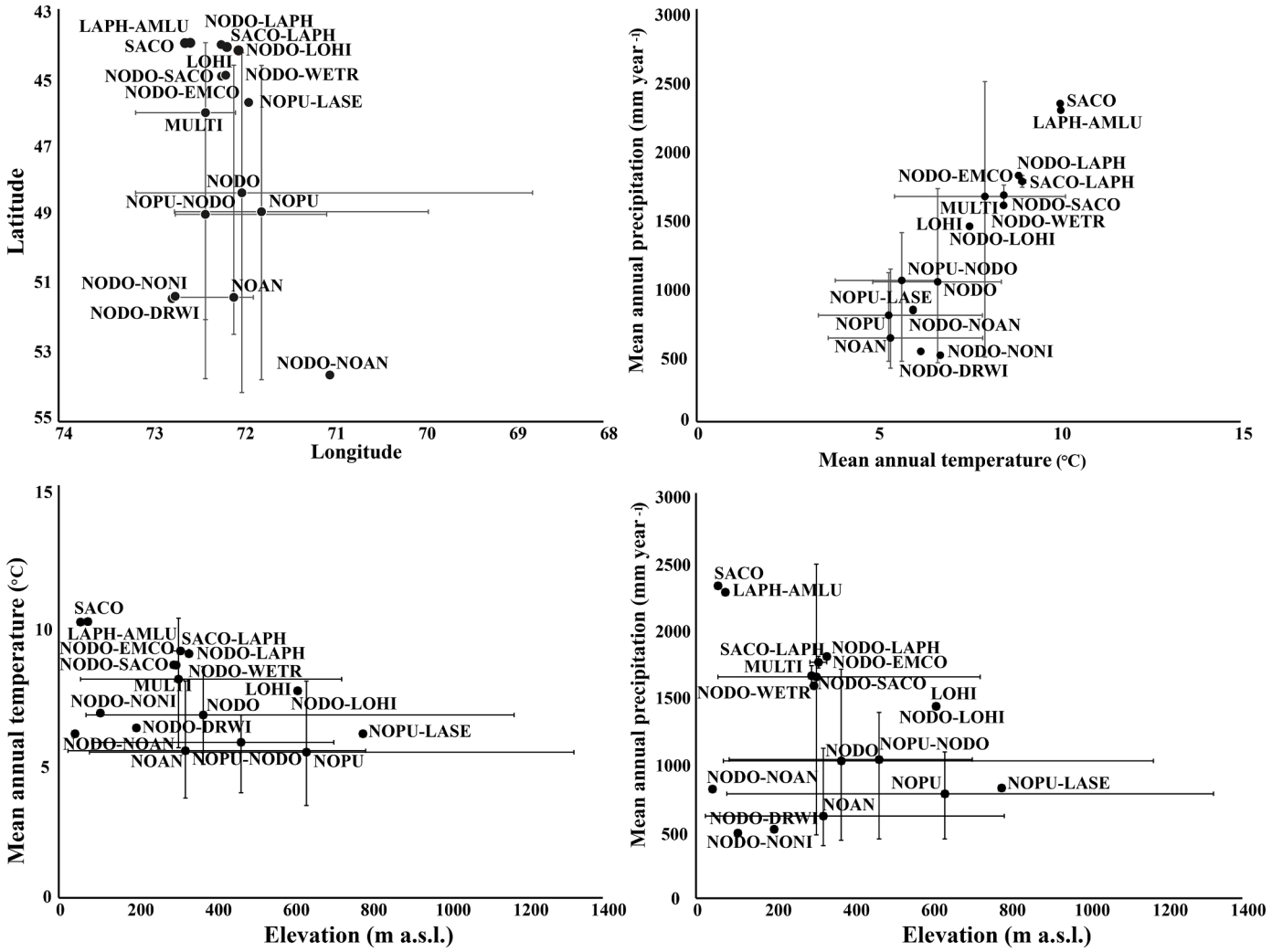

Fig. 6. Forest types (Level 2) characterization according to its geographical location (latitude and longitude), annual temperature (°C), annual precipitation (mm yr^{-1}), and elevation (m a.s.l.). Black dots represent the average values. X-axis bars: (min - mean) on the left, (max - mean) on the right; Y-axis: upper (min - mean), lower (max - mean). The species codes are presented in Fig. 4.

Table 1
Generalized linear models (GLM) of natural regeneration (response variables) based on the presence and pressure of livestock, Level 1 (mono-, bi-, and multi-specific forests), and Level 2 (forest types) classifications. AIC values followed the Akaike information criterion. Significant effects (p <0.05) were indicated in bold.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	**2.43**	**0.54**	**4.53**	**<0.001**
Livestock presence- Sheep-other	**-1.07**	**0.30**	**-3.56**	**<0.001**
Livestock presence- Cattle	-0.38	0.20	-1.93	0.054
Livestock pressure- Non-livestock	-0.78	0.42	-1.87	0.061
Livestock pressure- Low	-0.79	0.40	-1.97	0.050
Livestock pressure- Middle	-0.28	0.38	-0.74	0.461
Level 1 Monospecific	-0.49	0.36	-1.38	0.166
Level 1 Multispecific	-0.07	0.30	-0.24	0.811
Level 2 NOPU	**1.14**	**0.18**	**6.25**	**<0.001**
Level 2 OTHER	-0.12	0.36	-0.34	0.735

NOPU (*Nothofagus pumilio*) and OTHER (other deciduous and/or evergreen spp.).

effect size of both forest types (Hedges' $g > 0.51$) exhibited a similar pattern as was described earlier (Fig. 7). For the OTHER category, the effect size of low basal area and livestock on natural regeneration was smaller than the other treatments (Hedges' $g = 0.28$).

Table 2
Natural regeneration (n x 10,000 ha^{-1}) was classified according to livestock (presence and pressure) and Level 1 and 2 classifications. Data were presented as mean values (Mean±EE) and adjusted means values (Adjusted mean±EE) with standard errors generated by GLM. Letters indicate significant differences with the LSD test ($p < 0.05$). Significant effects are shown in bold.

Factor	Level	Plots	Mean±EE	Adj. mean±EE
Livestock presence	Non-livestock	83	8.01±1.61	**8.31±1.60 a**
	Cattle	46	4.61±0.81	**5.69±1.30 a**
	Cattle-horse	44	8.10±1.98	**8.31±1.67 a**
	Sheep-other	22	3.28±0.50	**2.84±0.75 b**
Livestock pressure	Non-livestock	83	8.01±1.21	4.21±0.82
	Low	78	5.27±0.71	4.15±0.83
	Middle	25	7.68±2.46	6.94±1.53
	High	9	4.17±1.01	9.19±3.46
Level 1	Monospecific	152	7.51±0.84	6.49±2.18
	Bispecific	29	3.86±0.65	6.98±1.97
	Multispecific	14	3.93±1.28	4.26±0.60
Level 2	NOAN	36	2.89±0.33	**4.11±1.17 a**
	NOPU	106	9.6 ± 1.14	**12.91±3.31 b**
	OTHER	53	3.57±0.49	**3.64±0.61 a**

NOAN (*Nothofagus antarctica*), NOPU (*N. pumilio*) and OTHER (other deciduous and/or evergreen spp.).

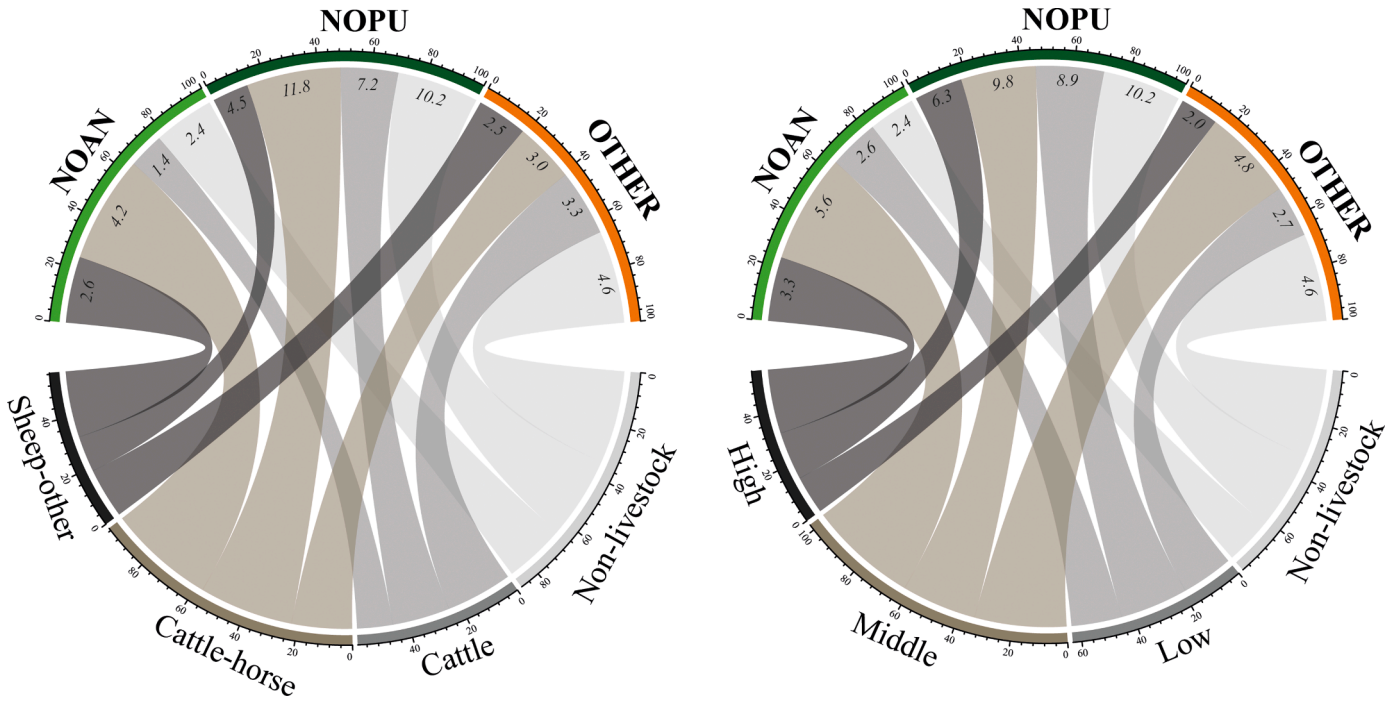

Fig. 7. Relationship between natural regeneration of the different forest types studied and livestock presence (left) or pressure (right). The coloured ribbons represent the various relationships, where the numbers in italic correspond to the regeneration (10,000 plants ha^{-1}), and peripheral numbers to the regeneration presented in the different forest types (%). NOAN = *Nothofagus antarctica*, NOPU = *N. pumilio*, and OTHER = other deciduous and/or evergreen species.

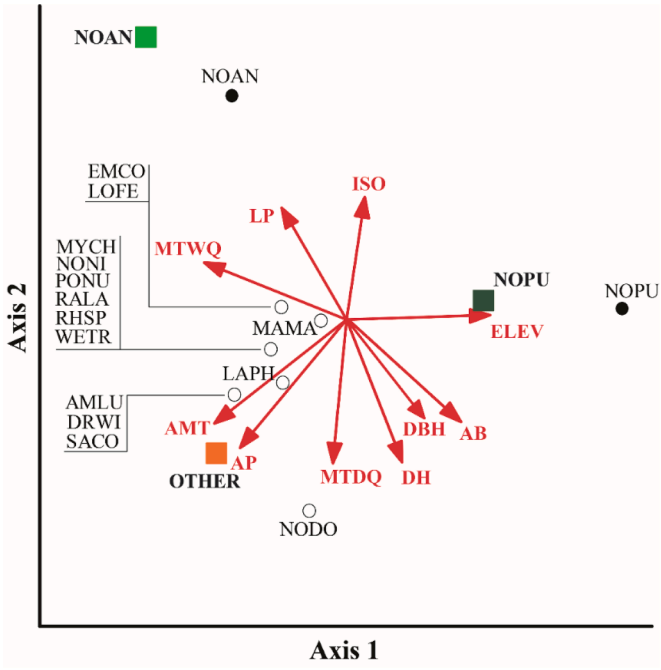

Fig. 8. PCA analysis illustrating the relationships between natural regeneration (white dots = evergreen, black dots = deciduous), forest types (coloured squares), and environmental variables (red arrows) using dummy variables. NOAN = *Nothofagus antarctica*, NODO = *N. dombeyi*, NOPU = *N. pumilio*, OTHER = other deciduous and evergreen or both species, AMT = Annual mean temperature, AP = Annual precipitation, BA = Basal area, DBH = diameter at breast height, DH = Dominant height, ELEV = Elevation, ISO = Isothermality, LP = Livestock pressure, MTDQ = Mean temperature of the driest quarter, MTWQ = mean temperature of wettest quarter. The species codes are shown in Fig. 4.

4. Discussion

4.1. Chilean Austral Macrozone forest types

In this study, we identified a greater richness of forest types for the Austral Macrozone (43° to 56° SL), which provides a clearer understanding of the region's native forests based on NFI data. This richness was significantly higher than the three basic forest types described for the native forests in this area of Chile (lenga, evergreen, coihue de Magallanes). This information is an example of why avoiding subjective interpretations of forest types and, consequently, the proposed forest management and conservation is essential. Previous studies in the northern hemisphere have highlighted the challenges in accurately characterizing forest types based on vernacular recognition and the potential for discrepancies in field data interpretation (Duncker et al., 2012; Cheng and Wang, 2019; De Cáceres et al., 2019). In our study, for instance, the designation of evergreen forest (siempreverde) can be misleading, particularly when considering *Nothofagus* species (e.g., *N. dombeyi*) alongside other evergreen species such as L. *philippiana, D. winteri, S. conspicua*, among others. This misleading suggests that when characterizing forest types in an NFI, several discrepancies in the interpretation of field data may arise (Heym et al., 2021; Tewari, 2016; Costanza et al., 2018; Temperli et al., 2022), leading to underestimation or overestimation of forest masses based on vernacular recognition of the different forest types (Álvarez-González et al., 2014; Hościło and Lewandowska, 2019; Nesha et al., 2022; and see Table S2). In our results, this was particularly evident when *N. pumilio* was reported in a plot since the forest type was classified as lenga regardless of its basal area dominance compared to other species (e.g., mixed forests with *N. dombeyi* or *N. antarctica*). The particular case of *N. antarctica* was even more striking, as even if the species forms pure forests, it is classified as a lenga forest type, assuming silvicultural practices similar to *N. pumilio*. However, this species was mainly used under silvopastoral management (Peri et al., 2017; Martínez Pastur et al., 2022).

In this context, the traditional typologies used in the Chilean Austral Macrozone are arbitrary (e.g., NOPU and NOAN were grouped together)

Table 3
Hedges' *g* effect sizes of livestock over natural regeneration considering the basal area in the studied forest types (NOAN, NOPU, OTHER). Medium and large effect sizes are shown in bold.

		Non-livestock			Livestock			
Basal area	Factor	Mean	SD	Plots	Mean	SD	Plots	Hedges' *g*
High	NOAN	ND	ND	ND	1.3	0.4	5	ND
	NOPU	12.6	15.2	34	9.8	10.9	43	0.22
	OTHER	6.0	4.6	11	3.5	3.7	26	**0.63**
Medium	NOAN	3.3	0.7	2	3.3	0.3	2	0.00
	NOPU	7.9	5.1	14	ND	ND	ND	ND
	OTHER	2.3	1.4	3	2.3	0.7	8	0.00
Low	NOAN	2.2	1.4	9	3.6	2.2	18	**0.71**
	NOPU	2.7	1.6	7	3.9	2.9	7	**0.51**
	OTHER	1.9	0.8	3	2.2	1.3	3	0.28
Overall		8.0	11.0	83	5.7	7.8	112	0.25

NOAN = *Nothofagus antarctica*, NOPU = *N. pumilio*, OTHER = other deciduous and/or evergreen species, ND = no data.

and not based on logical criteria, aiming to describe communities based on biometry or ecological parameters (e.g., evergreen forests). For example, this study showed that species such as NOAN, NOPU, and NODO occurred as mono-specific forests and in combinations typical of bi-specific forests. Therefore, here, we propose a new classification based on NFI data (e.g., forest structure) with an intuitive approach that can be applied administratively and scientifically for different purposes. Poorly planned map legends do not accurately represent the existence of forest types at different locations, leading to the implementation of biased management or conservation proposals (Heym et al., 2012; Costanza et al., 2018; Nesha et al., 2022). This lack of relevance has administrative implications (e.g., what to do with irrelevant forest types) and scientific implications (e.g., low representativeness) (CIEFAP and MAyDS, 2016; Costanza et al., 2018; Wiener et al., 2021; Xu et al., 2022). For example, most forest types were found in the northern part of the Macrozone (see Fig. 6), decreasing towards the south. This highlights areas that have not been considered, such as the northern part of the region, where there was an extraordinary diversity of forest types (far from pure communities).

4.2. Relationship between forest types, climate, and topography

Understanding forest types extends beyond the precipitation or temperature gradient analysis, as elevation plays a crucial role in shaping their characteristics. In this regard, the classification of NFI categories needs to incorporate ecological criteria established through empirical research and ecological principles (CIEFAP and MAyDS, 2016; Schulze et al., 2019; Hoover et al., 2020). The scientific comprehension of forests is influenced by various factors, encompassing climate, soil quality, geography, and species interactions (Donoso, 1981, 1993; Schulze et al., 2019). Hence, a comprehensive understanding of forests in NFI necessitates considering broader ecological factors (Bahamondez et al., 2016; CIEFAP and MAyDS, 2016; Fuentealba et al., 2021). In our study, forest structure variables were closely related to regeneration, where the forest types NOPU and OTHER showed greater regeneration in forests with higher dominant height, DBH, and total basal area. Previous studies described that NOPU regeneration is higher when seedlings establish under open canopies, growing faster in response to light availability (Agestam et al., 2003; Gea-Izquierdo et al., 2004).

Additionally, studies in more northern areas of Chile have shown that species belonging to evergreen forests, such as DRWI and EMCO, act as pioneer species (establishing rapidly after severe disturbances). In contrast, species like AMLU and SACO prefer more closed and protected environments for establishment (Romero Mieres et al., 2014). On the other hand, the regeneration of NOAN is higher in forests with lower dominant height, DBH, and total basal area (more open and shorter forests). This may be because NOAN, under animal husbandry and anthropic pressure, tends to regenerate through agamic means, where large trees (old-growth) sprout before dying. It is also described that the effect of light levels on NOAN regeneration is crucial, as forests with higher tree coverage have been observed to have a greater number of seedling incorporations (Peri et al., 2016).

4.3. The effect of animal husbandry on analyzed forests

This study was conducted in the Austral Macrozone of Chile using data from the NFI, where the animal husbandry (cattle, horses, and sheep) was mainly observed in forests of *Nothofagus antarctica* (ñire) and *N. pumilio* (lenga). In this study, we present controversial results regarding native forests with animal husbandry. Despite the presence of livestock in the studied forests, it did not seem to be a conclusive limitation for natural regeneration. However, according to previous studies (e.g., Mazzini et al., 2018), high levels of overgrazing (which were not measured in this study) could indeed affect regeneration. Research has described that damage to regeneration is mainly influenced by factors such as seedling height (taller than those used in this study), stand density, and the severity of grazing pressure (Asner et al., 2004; Echevarría et al., 2014). Besides, the sustainability of native forests as a managed species may not only depend on the conditions of the forest itself but also on the collective set of surrounding environments that comprise it (e.g., the introduction of native or unwanted exotic plants from other environments) (Huertas Herrera et al., 2018). Also, it is known that animal husbandry significantly impacts the composition of herbaceous plants in native forests (Sánchez-Jardón et al., 2014; Huertas Herrera et al., 2018), which can lead to a loss of diversity that inadvertently results in the invasion of unwanted exotic species (Rusch and Varela, 2019).

The Principal Component Analysis (PCA) showed that the higher natural regeneration of deciduous species could be explained by anthropogenic factors such as grazing pressure (NOAN) and topographic factors such as elevation (NOPU). In comparison, bioclimatic variables mainly explain the higher natural regeneration of evergreen species. Therefore, animal husbandry in native forests is not necessarily a limiting factor for their regeneration. Sustainable animal husbandry in native forests, such as NOPU, is possible within certain limits where it can coexist with natural forest regeneration. In Echevarría et al. (2014), seedling establishments of NOAN with high and low grazing pressure were compared, describing that the levels of damage caused by cattle browsing on the lateral growth of seedlings were identical in both situations. Although total livestock exclusion is recommended for ecosystem recovery, this research suggests sustainable animal husbandry is possible in forest types like NOAN and other forest types like NOPU or OTHER. Landscape-scale integration between production and conservation is recommended to address relevant issues in these temperate forest ecosystems. Assessing vegetation responses to human activities, like animal husbandry, is crucial in formulating effective management and conservation strategies.

5. Concluding remarks

The work follows an approach from the global to the specific. Therefore, it started with general levels (types of mono, bi, and multi-forests) and then moved to more detailed levels of forest types by species (Level 2). The classifications and analysis of the levels of study of forest types serve a dual purpose. Both categories exhibit distinct ecological values and offer diverse potentials for management and conservation purposes. Through these analyses, we could emphasize the practicality of each approach. The first dimension (Level 1) assesses the homogeneity/heterogeneity of species cover, a critical concept in defining management types. On the other hand, the second dimension (Level 2) emphasizes the species composition within various stands, rendering it more valuable for conservation efforts.

The study revealed the existence of valuable richness of different forest types in the Macrozone. It is necessary to have a map legend of forest types that somehow reveals the complexities and richness of forests at a regional scale. These complexities can be useful in administrative terms to guide forest management towards current national and international challenges (e.g., animal husbandry public policies aimed at countering climate change) since vernacular denominations of forest types overlook the existence of forest masses directly related to sustainable forest use (e.g., animals in forests), such as those forests contained within a specific forest type (e.g., ñire forests as part of the lenga forest type). This approach suggests that it is necessary to avoid definitions of forest types based on pre-existing cognitive descriptions of a forest. The biometrics and forest inventories expand the capabilities to define forest types (Schulze et al., 2019; Sebrala et al., 2022).

In this context, the appropriate use of forest classifications is relevant in forest policies, as generalized forest types often have particularities for their management and conservation that are not considered. For example, when forest policies are established for a region, they ultimately influence more than one forest type; this can affect more vulnerable or less representative forest types, as many forest regulations focus on the most abundant species, such as NOPU. This consideration is important to define what needs to be conserved (e.g., more vulnerable forest types). However, forests in the region are exploited for animal husbandry and timber extraction, usually through practices adopted from other regions of the world. This lack of local perception generates negative synergies that lead to an overuse of ecosystems beyond their resilience. This situation increases forest pressure due to inappropriate management policies (Gea-Izquierdo et al., 2004). The aforementioned is incompatible with the current challenges of sustainable forest management agreed upon by Chile with global commitments (e.g., climate change), as the existing typology lacks a proper applicable legal intervention for forests.

Science is fundamental in characterizing, understanding, and improving policies according to the productive and environmental context (Fuentealba et al., 2021). Technical-scientific knowledge helps to understand natural resources and improve forest management in practice. Additionally, this knowledge can be translated into policies and the participation of scientific actors in forest policies (Soler et al., 2021). This work demonstrates the need to create a forest redefinition that ensures the representativeness of forest subtypes through structural parameters and species composition to value forest diversity. It is necessary to address technical and legal aspects within the current framework (Salinas et al., 2017). Adopting innovative forest management strategies in line with scientific knowledge and considering climate change is vital.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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