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ORIGINAL RESEARCH ARTICLE

Progressive fragmentation and loss of natural forest habitat in one of the world's biodiversity hotspots

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ABSTRACT

Knowledge of the state of fragmentation and transformation of a forested landscape is crucial for proper planning and biodiversity conservation. Chile is one of the world's biodiversity hotspots; within it is the Nahuelbuta mountain range, which is considered an area of high biodiversity value and intense anthropic pressure. Despite this, there is no precise information on the degree of transformation of its landscape and its conservation status. The objective of this work was to evaluate the state of the landscape and the spatio-temporal changes of the native forests in this mountain range. Using Landsat images from 1986 and 2011, thematic maps of land use were generated. A 33% loss of native forest in 25 years was observed, mainly associated to the substitution by forest plantations. Changes in the spatial patterns of land cover and land use reveal a profound transformation of the landscape and advanced fragmentation of forests. We discuss how these patterns of change threaten the persistence of several endemic species at high risk of extinction. If these anthropogenic processes continue, these species could face an increased risk of extinction.

Keywords: Deforestation; Nahuelbuta Mountain Range; Diversity; Endemism; Landscape-scale Conservation; Effect of Exotic Plantations

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1. Introduction

The state of transformation of a forested landscape is characterized by the degree of habitat destruction and modification, the rate of deforestation, patterns of natural forest fragmentation and changes in the matrix[1,2]. In this sense, one can find little modified landscapes, with low deforestation rates, and extensive and well-connected areas of native forests[1], or highly fragmented and modified landscapes, where forest cover occupies a reduced area of the landscape, with scattered, isolated and non-connected habitat fragments, and a matrix composed of anthropogenic uses[3,4]. Knowledge of the state of transformation of a landscape is a crucial antecedent for proper landscape planning, management and restoration, as it indicates the degree of integrity or functionality of the landscape and the main attributes that need to be maintained or improved for the conservation of biodiversity and human well-being[5]. These antecedents are especially important in landscapes with high diversity and endemism of flora and fauna species, but with substantial losses of forested habitats[4].

Fragmentation of natural forests is one of the main causes of biodiversity loss in the world[6]. The main effects of fragmentation at the landscape level are reduction of forest habitat size and quality, increase in edge and number of patches, and loss of connectivity[7,8]. The edge of a patch in the landscape is defined as the transition zone between habitats, and its perception varies depending on the observer, organism or variable studied[9]. Forest fragments can have smooth or abrupt edges, depending on the degree of contrast between habitats, which plays a critical role in the ability of species to adapt and move within disturbed habitats, the resilience of the forest and the penetration of edge effects that originate a deterioration in habitat quality in regression[8,10,11]. The reduction in forest fragment size generates changes in composition and structure at the community level[12,13], modifying population dynamics and various ecological processes[14,15] that, together with isolation and decreased functional connectivity, have negative effects on the persistence of species populations[8,16]. It has been found that the continued fragmentation and loss of tropical and temperate forests have affected forest richness and structure, bird abundance and diversity, insect community assemblages, and the persistence of mammal populations, among others[12,17-20].

Hotspots are regions with global priority for conservation due to their high degree of endemism and strong anthropogenic impact; alarming figures indicate that more than 85% of the original habitat present in hotspots has been destroyed[21]. Currently, 35 hotspots have been defined, among which the hotspot "Chilean winter rainfall-Valdivian forests" is characterized by hosting a total of 3,893 native vascular plant species, 50% of them endemic to the hotspot itself and containing more than half of the temperate forests of the southern hemisphere[21]. One of the most unique, least protected and most altered landscapes of the Chilean hotspot is that present in the Nahuelbuta mountain range ("cordillera", hereafter)[22]. This area is considered by some scientists as an area of high conservation value and world biodiversity reserve, due to its high levels of species diversity and endemism, and physical characteristics that favored the persistence of some species, even during the last glaciation[22,23]. The high species richness and endemism of this area is attributed to the fact that the deciduous forests and scrublands characteristic of the Mediterranean zone of northern Chile converge with the evergreen Valdivian vegetation of southern Chile, forming a unique eco-tonal ecosystem and for having remnant species from the Mesozoic of Gondwanic origin, and Tertiary species of tropical origin[22].

Despite its high value for biodiversity conservation, various anthropic processes, such as the replacement of native forest by plantations of exotic species, forest fires, firewood extraction, intensive agriculture and overexploitation of native species, have been associated with the degradation and loss of the natural forests of this "cordillera"[22,23]; which has affected different species of flora and fauna endemic to Chile and present in the "cordillera", which are threatened and at risk of extinction, such as the trees, queule (Gomortega keule (Mol.) Baillon) and pitao (Pitavia punctata (R. et P.) Mol.), amphibians, Darwin's frog (Rhinoderma darwini) and Contulmo toad (Eupsohus contulmoensis), among mammals, Darwin's fox (Lycalopex fulvipes) and the marsupial (Dromiciops gliroides)[23,24], among many others. Although there are punctual studies of the transformation of Chile's coastal landscapes[25], there are no spatio-temporal studies on the state of transformation of the "cordillera", and in particular, of the changes in the spatial patterns of its native forests. Because of this, there is no basic information to plan conservation and restoration actions or strategies at a landscape scale.

The objective of this work is to evaluate the state of the landscape and the spatio-temporal changes of native forests in the "cordillera", and from these results, to discuss the implications that such changes have on the persistence of several endangered species of flora and fauna of the "cordillera", dependent on native forest habitats. It is possible to expect that due to the constant loss and substitution of native forest by forest plantations of exotic species and habilitation of areas for agriculture, the "cordillera" is in an advanced state of transformation and fragmentation of natural forests.

2. Materials and methods

The "cordillera" is located between the Biobío River and the Imperial River, in the administrative regions of Biobío and La Araucanía, respectively, and extends for 200 km in a north-south direction, reaching a maximum altitude of 1,530 m asl (**Fig-**

ure 1). Precipitation is 80% concentrated in the autumn and winter months, increasing in 2 gradients, one latitudinal (north-south) and the other longitudinal (west-east), with frequent snowfalls above 1,000 m asl in the winter months[26].

Since there is no study that precisely defines the limits of the "cordillera", in the present work, limits were established based on geological, pedological, vegetational and altimetric criteria. The geological criterion considers the formation of the "cordillera" in the upper Paleozoic, being much older than the Andes, which dates from the end of the Tertiary[27]. This delimitation excluded marine sedimentary platform sequences and pyroclastic deposits associated with collapse calderas[27,28]. The pedology of the "cordillera" corresponds mostly to ultisols of the Nahuelbuta Association series generated from metamorphic rocks, of clayey, silty-clay loam texture, deep and generally of steep topography[29]. Redelimitation from vegetational formations consisted of smoothing and closing the edges of the product obtained from the previous redelimitations, for which the classification of vegetation floors proposed by Luebert and Pliscoff was used[30]. The altimetric limit was based on the elevation of 200 m asl, due to its spatial congruence with the other criteria analyzed.

To generate thematic maps of land use, Landsat satellite images from spring and summer 1986 (TM) and 2011 (ETM+) were used, with a cloud cover of less than 10%. To facilitate their processing and carry out quantitative comparison of land use coverages, the images were projected at a spatial resolution of 30 × 30 m/pixel and subsequently geometrically, atmospherically and topographically corrected[31]. By means of the C-factor methodology, shadows cast by site topography were removed[32]. To increase the accuracy of the classification, the vegetation indices NDVI, SR, SAVI and LSWI were used[33-35].

A supervised classification was performed for each image using the maximum likelihood statistical method and training points, which represent the patterns of land cover types. A total of 300 training points were taken in different field bells for the classification of the most recent images. While for the 1986 images, land cover maps generated by previous studies[36,37] and local consultation of land

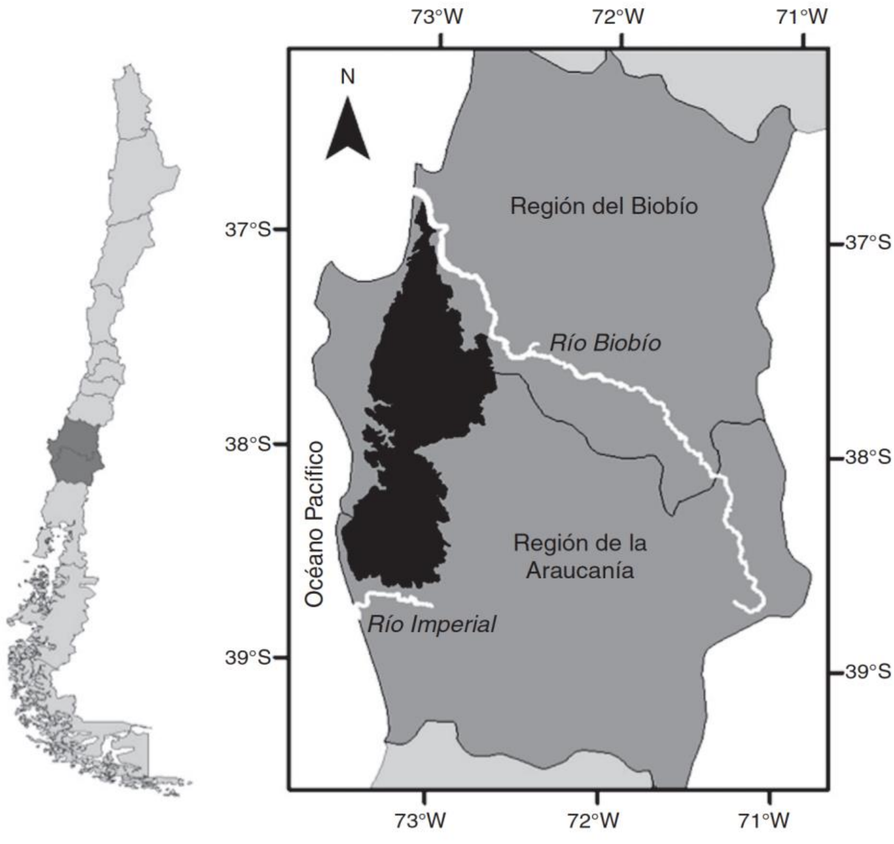

Figure 1. Location of the Nahuelbuta mountain range between the Biob ó River and the Imperial River in the administrative regions of Biob ó and La Araucan á, Chile.

Table 1. Landscape metrics used for the analysis of spatial patterns of native forests in the Nahuelbuta mountain range[38]

Class	Metrics	Description	Unit of measure	Range of variation
Area, density and border	Patch area	Area of each patch of native forest in the landscape	Hectares	0 and no limit
	Larger patch index	Percentage of the area of the largest native forest patch in relation to the total area of the landscape	Percentage	0 < LPI ≤ 100
	Patch density	Number of native forest patches per 100 hectares	Numeric	PD > 0
	Edge density	Density of edge length of native forest patches in the landscape	Meters per hectare	ED ≥ 0, no limit
Form	Average perimeter-area ratio	Relationship between perimeter and area	None	FOR > 0 and without limit
Core area	Average core area	Core area of the native forest, specified by the depth of the edge according to the proximity of the patch to other land uses	Hectares	CORE ≥ 0 and no limit
Isolation proximity	Average distance to nearest neighbor	Proximity of native forest patches, based on weighted average distance	Meters	ENN > 0 and no limit
Contrast	Area-weighted mean edge contrast	Degree of contrast of native forest with respect to its density. The contrast represents the magnitude of the difference between native forest and other land uses	Percentage	0 ≤ ECON ≤ 100
Contagion interspersion	Aggregation index	Proportional deviation of adjacencies involving native forest class from that expected for a spatially random distribution	Percentage	-1_CLUMPY_1

use covers that showed no change of use in the last 20 years were used. The classification accuracy of the images was calculated by means of confusion matrices, from a range of between 60 and 90 validation points taken in the field and recent aerial photographs, for each type of cover, of each satellite image. A classification filter was applied to each of the cover classes present in order to exclude patches with less than 4 pixels.

The land cover or land use classes of the "cordillera" landscape identified from each image were: 1) primary native forest (old-growth forest originating from natural succession); 2) secondary native forest (forest regeneration following disturbance); 3) stunted forest; 4) arborescent scrub; 5) shrub-land; 6) exotic forest plantations (commercial plantations); 7) agricultural land (agricultural crops, grasslands and livestock use areas); and 8) other uses and cover (water bodies, urban, cloud and shade).

The transition from native forest cover to other land uses was analyzed using the Change Analysis module of the Land Change Modeler extension of the IDRISI software[39]. In the case of changes in native forests, the following formula was used to determine the annual deforestation rate:

$$P = \left[\frac{A_2^{\left(\frac{1}{(t_2 - t_1)}\right)}}{A_1} - 1\right] \times 100$$

where A_1 and A_2 are the area of native forest at time t_1 and t_2, respectively, and P is the percentage loss per year[40].

The current state of the landscape was analyzed based on the landscape change models proposed by McIntyre and Hobbs and Echeverrá *et al.*[1,2]. Specifically, the following variables were used: loss and fragmentation of native forests, deforestation rate, dominant landscape process, and changes in the matrix during the period studied. On the other hand, landscape transformation was measured as percentage of remaining habitat in terms of natural forests[2].

For the analysis of spatial patterns of native forest cover between 1986 and 2011, FRAGSTATS software[38] was used. The choice of the set of metrics to use was based on the review of several studies on landscape metrics that best expressed the spatial configuration of real landscapes, and were also representative of essential components of landscape structure such as: patch quality, patch edge, patch context in the landscape, and patch connectivity (**Table 1**)[5,41-44].

For the calculation of the contrast index, contrast weights were assigned between the edges of native forest patches and the other cover types present in the study area. The contrast weight of the edges was determined based on variables of vegetation composition and structure, measured in 13 sampling plots of 20 × 10 m. For the calculation of the core area, perpendicular distances were used from the edge to the center of the patch, which corresponded to the edge effect zone between the native forest and the other cover types. The distance assigned was based on the work of Laurance *et al*.[14], López-Barrera[9] and Lindenmayer and Fischer[8], considering that the degree of contrast between habitats (soft or abrupt edges) expresses the magnitude and distance of primary and secondary responses of the structure, composition and processes of the habitat to edge effects.

3. Results

Image classification. The accuracy of the 1986 classification was 87%, with the exotic plantation class being the least accurate, being confused with primary native forest cover. Primary native forests for 1986 had an accuracy of 88%, while secondary and stunted native forests had an accuracy of 86 and 87%, respectively. For 2011, the classification accuracy was estimated at 85%, with the arborescent shrubland class being the least accurate (77%). Plantation forests had 78% accuracy, while primary native forests obtained 86%, secondary native forests 85% and stunted forests 88%.

Loss of forest cover. The "cordillera" has an area of approximately 620,000 ha, of which 206,130 ha ±26.8 ha were native forests in 1986, decreasing to 137,700 ha ±19.3 ha in 2011 (**Figure 2**). In other words, in 25 years the forest cover decreased by 33.2% with a deforestation rate of 1.6% per year. The net loss was more intense in primary native forests than in secondary native forests, while stunted forests showed no loss. In 1986, primary native forests occupied only 8% of the total landscape (52,019 ha), reducing their area by half in 2011, with a deforestation rate of 2.6% per year (**Figure 2**). In comparison, secondary native forests presented a net loss of 43,000 ha, representing 28% of the original area in 1986 (152,200 ha), with a deforestation rate of 1.3% per year (**Figure 2**).

Regarding transitions from primary native forests, 68% of the net loss was due to substitution to plantations of exotic species and, to a lesser extent, degradation to secondary native forests (11%) and arborescent shrublands (12%). On the other hand, 95% of the changes in secondary native forest cover corresponded to substitution by plantations of exotic species. In this same study period (1986-2011), plantations of exotic species increased by almost 150% from 90,750 ha in 1986 to 251,250 ha in 2011, with an afforestation rate of 4.2% per year, being the predominant cover in 2011 (**Figure 2**).

Analysis of spatial patterns of native forest cover. Considerable changes were observed in the patch size distribution of forest cover during the period 1986–2011 (**Figure 3**). In 1986, 61% of the primary native forest area was in patches smaller than 50 ha, 22% in patches of 50 to 500 ha and 17% distributed in 7 patches larger than 500 ha (**Figure 3**). Subsequently, in 2011, of the 26,600 ha of existing primary native forest, 72% was distributed in patches smaller than 50 ha, 18% in patches of 50 to 500 ha and only 10% was distributed in 3 patches larger than 500 ha (**Figure 3**). In 2011, a single large patch of primary native forest of 1,120 ha was observed. Of the 25,420 ha of primary native forest deforested, 49% occurred in patches of less than 50 ha in area.

In relation to the secondary native forest, approximately 50% was in patches of less than 50 ha in area, with only one large fragment persisting over time, representing 4.3% of the total area of the landscape in 1986 and 4.5% in 2011 (**Figure 3**). In the study period, the secondary native forest presented an approximate regeneration of 5,680 ha, of which 82% occurred in patches of 2,000 to 5,000 ha. However, of the 43,000 ha of secondary native forest deforested, 53% of the loss occurred in patches of less than 50 ha in size.

From 1986 to 2011, there was an increase in the complexity of the shape of primary and secondary native forest fragments (**Table 2**). The degree of habitat contrast was greater in primary native forest

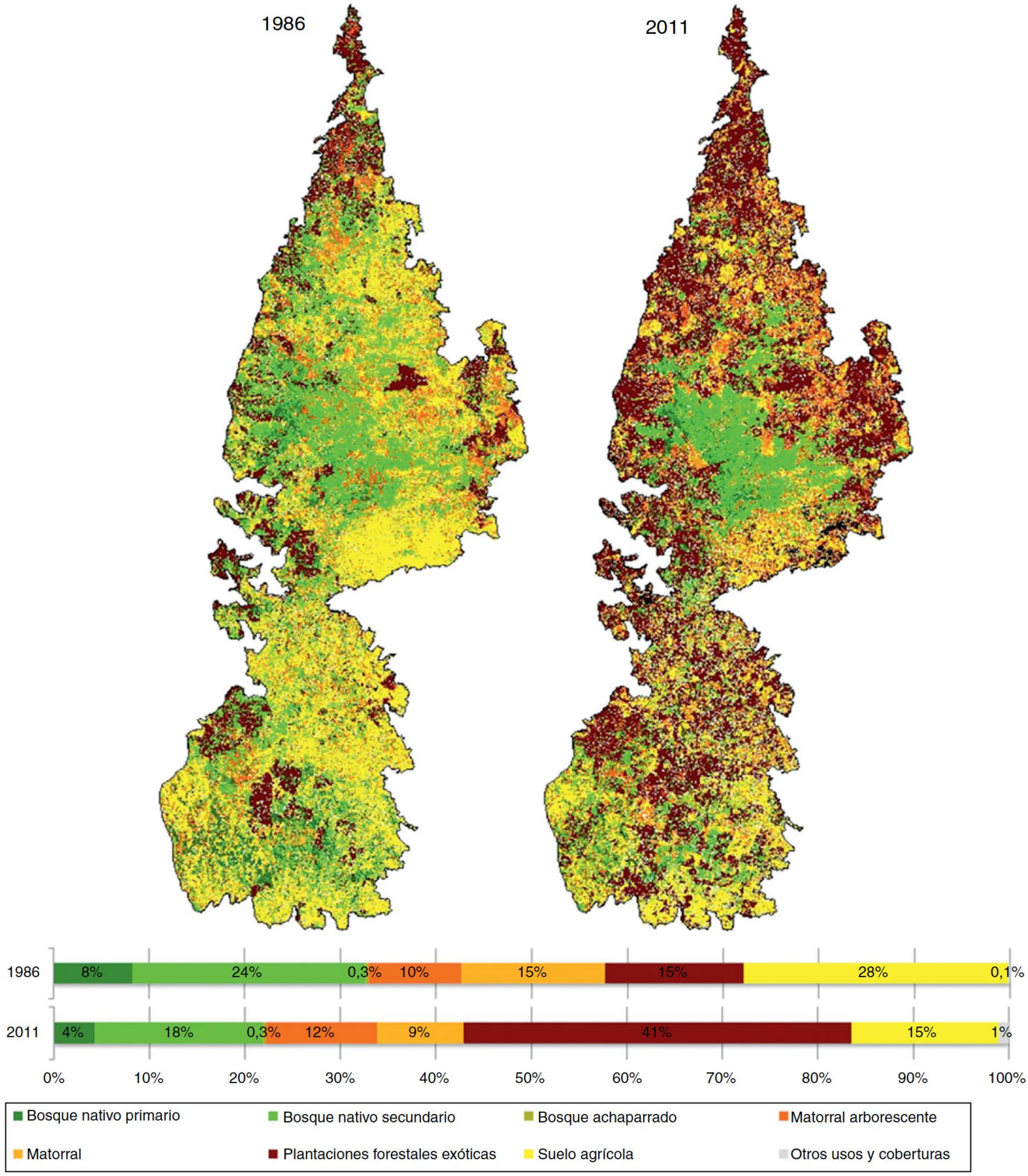

Figure 2. Spatio-temporal variation and percentage of the area occupied by land cover types in 1986 and 2011 in the Nahuelbuta mountain range.

than in secondary forest, with a slight tendency to decrease over time (**Table 2**). Stunted forests presented the lowest degree of contrast in the study period (1986 = 38%, 2011 = 29%) (**Table 2**).

In 1986, the density of primary and secondary native forest patches was 3.73 and 5.58, respectively (**Table 2**). In 2011, this index decreased to 2.51 fragments for primary native forest and 4.62 fragments for secondary native forest (**Table 2**). Similarly, edge density decreased from 1986 to 2011 for all 3 forest types, with the greatest edge reduction occurring in secondary native forest (**Table 2**).

An increase in the distance between primary and secondary native forest patches was observed (**Table 2**). The aggregation index of primary native forest decreased, while that of secondary native forest

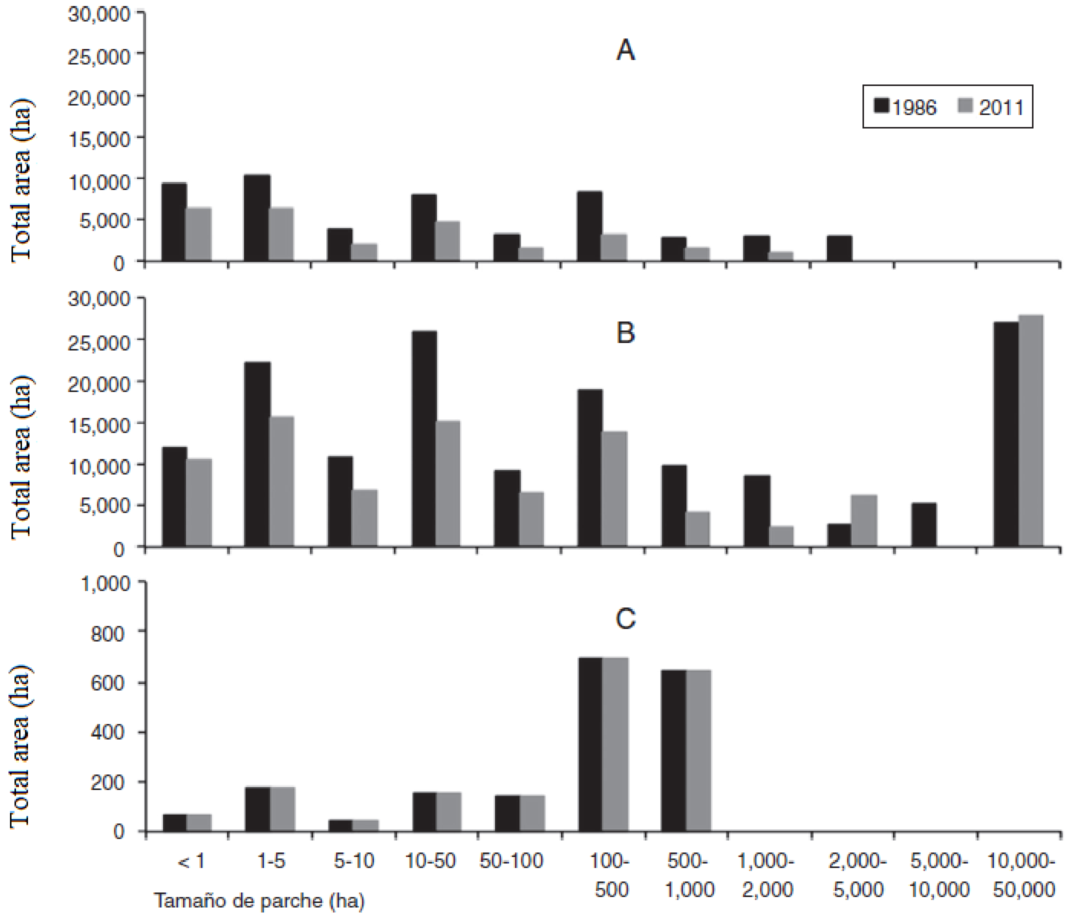

Figure 3. Temporal variation of patch size (ha) of primary **(A)**, secondary **(B)** and stunted **(C)** native forests in the Nahuelbuta mountain range.

increased (**Table 2**). However, there was no considerable variation in the aggregation index of forest fragments in the landscape. On the other hand, stunted forests did not show changes in the mean distance between fragments and in their aggregation index (**Table 2**).

The core area of primary native forest had a 4% loss, which is consistent with a 63% decrease in the area of the largest patch for this forest type (**Table 2**). In contrast, secondary native forest and stunted forest increased by 20% and 12% in core area, respectively (**Table 2**).

Table 2. Changes in landscape pattern indices in the Nahuelbuta mountain range at the class level between 1986 and 2011

Type of forest cover	Class	Contrast	Form	Area, density and border			Isolation proximity	Contagion interspersion	Core area
	Metrics	Area-weighted mean edge contrast	Average perimeter-area ratio	Patch density	Edge density	Larger patch index	Average distance to nearest neighbor	Aggregation index	Average core area
Primary native forest	1986	44.72	776.46	3.73	30.14	0.49	133.99	0.63	0.79
	2011	42.16	817.77	2.51	19.82	0.18	154.67	0.57	0.76
Secondary native forest	1986	60.17	731.04	5.58	76.45	4.33	93.01	0.59	0.85
	2011	56.70	785.56	4.62	55.54	4.52	105.09	0.62	1.06
Stunted forest	1986	38.20	654.97	0.04	0.65	0.10	113.14	0.79	4.09
	2011	29.03	654.97	0.04	0.61	0.10	113.14	0.79	4.64

4. Discussion

Loss of forest cover. The present study revealed a total loss of native forest of 33.2% at a deforestation rate of 1.6% per year between 1986 and 2011 in a landscape of high conservation value, located in a biodiversity hotspot. This loss was more intense in primary native forests (49%) than in secondary native forests (28%), and occurred mainly due to substitution to exotic forest plantations. A loss of native forest similar to that of the present study was also observed in the Chilean hotspot, between the regions of Biobío and La Araucanía in the period 1979–2000, where the net forest loss was 28.2% at a deforestation rate of 1.6% per year[45]. Of this percentage of loss, 71.7% was due to forest substitution by exotic forest plantations[45]. On the other hand, in the Chilean coastal landscape of the Maule region, between 1975 and 2000, a loss of 67% of native forests was estimated, double that recorded in the present study, at a deforestation rate of 4.5% per year, mainly as a consequence of substitution by exotic forest plantations[3]. This reflects the constant loss of native forest by substitution to exotic forest plantations and the current absence of large extensions of native coastal forests in Chilean hotspot landscapes.

Loss of forest habitat in biodiversity hotspots has also been reported in other areas of the world in recent decades. For example, in the hotspot of Limón province in Costa Rica, deforestation in 1997 was 54,830 ha, equivalent to 8.4% of the forest cover existing in 1986[46]. Higher percentages of deforestation than estimated in the "mountain range" were observed in the Eastern Arc mountain hotspot of Tanzania, where natural evergreen forests and wooded savannas disappeared by 48% between 1975 and 2000[47], and in the Ecuador hotspot, located in the provinces of Loja and Zamora Chinchipe, where forest cover loss was 46% between 1976 and 2008[48].

Landscape condition. The landscape exhibited a deforestation rate of 2.6% per year for primary native forest and 1.3% per year for secondary native forest, with 22% of the forest cover persisting in 2011. Likewise, there was a decrease in the density of patches and edges of primary and secondary native forest, an increase in the distance between patches, and an increase in the matrix dominated by plantations of exotic species. According to these results, the "cordillera" corresponds to an advanced stage of landscape transformation[1,2]. In this landscape state, the loss of forest fragments dominates over forest partitioning and usually occurs subsequent to intense forest fragmentation processes[1,2]. Very different was observed in India between 1975 and 2005[49], and in the biodiversity hotspot in southern Ecuador[48], between 1976 and 2008, where there was a reduction and division of large forest patches, while there was an increase in the number of patches, length and edge density, a pattern characteristic of initial phases of fragmentation[40].

If the trajectory of the studied landscape continues, and without planning and management measures for the conservation, protection and restoration of forest ecosystems, a considerable loss of forest cover is expected in the future, with a decrease in the rate of deforestation. Likewise, if the current rate of afforestation with exotic species remains constant at the estimated rate (4.2% per year), it is possible to expect a greater homogenization of the landscape with one or two species of commercial interest, turning the "cordillera" into a relictual landscape, severely deforested, with small patches of highly modified native forest, isolated and without connectivity, surrounded by highly contrasting land uses[1,2]. In this state, the slight increase in secondary native forests and changes in trajectories would indicate regeneration in abandoned agricultural areas, as has been reported in the commune of Ancud, Los Lagos region, Chile[58].

4.1 Changes in the spatial pattern of forest cover and implications for biodiversity conservation

Impacts of the decrease in the size of habitat patches. The rapid process of deforestation in the "cordillera" caused the loss of large fragments of native primary and secondary forest in just 25 years, with few patches larger than 1,000 ha and 50% of the forest area in patches smaller than 50 ha. In this sense, in the coastal landscape of the Maule-Cobquecura river in Chile (north of the "cordillera"), it was found that during the period 1975–2000 in the first year of study, 44% of the forest area was concentrated in a large patch of between 20,000 and 100,000 ha. By 2000, 69% of the forests were in patches of less than 100 ha and only 3% of the forest area was in patches larger than 1,000 ha[3]. This reduction in the size of native forest patches in Chilean landscapes may affect the availability of habitat for various species that require large areas to persist[14,19,59]. In this sense, it has been reported that carnivore species present in the "cordillera", such as the puma (*Puma concolor*)

Table 3. Linkage between spatial patterns reported in the present study and ecological processes of threatened species in the Nahuelbuta mountain range

Spatial pattern of native forests in the Nahuelbuta mountain range reported by the present study	Ecological impacts reported by other studies for endangered species in the Nahuelbuta mountain range				
	Species	**Current category**	**Source**	**Impacts**	**References**
Loss of surface area. Reduction of the number of patches. Few patches with area greater than 1,000 ha. 50% of forest area in patches < 50 ha. Decrease of the area of the largest patch of primary native forest	Lycalopex culpaeus Lycalopex griseus Lycalopex fulvipes Leopardus guigna Puma concolor Galictis cuja Conepatus chinga	Vulnerable Minor concern In danger Vulnerable Near threatened Vulnerable Rare	RCE RCE RCE RCE RCE CAZA CAZA	Loss of forest cover reduces habitat for native carnivore species that prefer large patches of mature forest. Increased levels of spatial overlap, competition for prey and territory are expected.	Moreira-Arce *et al*.[50]
	Campephilus magellanicus	In danger	RCE	The lack of patches of primary native forest with large areas of interior habitat in the landscape could affect the survival of the species. To form family groups, it requires patches with an area greater than 100 ha of mature forests of the genus Nothofagus. Between 1986 and 2011, a 56.7% reduction of the species' habitat in Nahuelbuta was estimated.	Llabrés[51]
	Birds	-	-	The composition of avifauna is significantly different between forest habitat types, which could be attributed to differences in composition and structure between habitats, as a result of landscape fragmentation processes.	Fontúrbel and Jiménez[52]
	Scelorchilus rubecula Scytalopus magellanicus	Minor concern Minor concern	UICN UICN	The composition and structure of the understory is a key component of species habitat. Reduction in understory complexity and diversity affects site availability for species.	Moreno-García *et al.* [53]
	L. culpaeus *L*. griseus *L*. fulvipes *L*. guigna	Vulnerable Minor concern In danger Vulnerable	RCE RCE RCE RCE	The probability of site use by specialist carnivores increases as structural as the structural diversity of the habitat diversity of the habitat increases. Therefore, changes in vegetation structure, as a result of fragmentation processes, decrease the availability and use of habitats for the species.	Moreira-Arce *et al*.[54]
High rate of contrast between primary and secondary native forests. Increase in the complexity of the shape of the fragments.	Alsodes vanzolinii	Endangered-rare	RCE	Their populations are associated with streams in small remnant patches of native forest surrounded by forest plantations of exotic species. This affects the movement of amphibians in the landscape, which depend on connected habitats for the development of their life cycle.	Rabanal and Alarcón[55]
	Telmatobufo bullocki	Vulnerable-rare	RCE	Erosion processes related to harvesting and management of forest plantations sediment water bodies associated with their habitat and biophysical changes, which limits food resources and eliminates adequate conditions for their reproduction.	Soto-Azat *et al*.[56]
Increased isolation between primary and secondary native forest fragments	Pitavia punctata	In danger	RCE	Degraded habitats, isolated and surrounded by plantations of exotic species. Low genetic diversity, high degree of genetic differentiation between localities and a high level of isolation, which makes the species sensitive to fragmentation and increases its risk of extinction.	Venegas[57]

and Darwin's fox, show preferences for mature native forest habitats and large patches, which would concentrate their populations in a few patches in the "cordillera", increasing the levels of spatial overlap between carnivore species, including the feral dog, and competition for prey and territory[50] (**Table 3**). For their part, threatened bird species present in the "cordillera" and associated with primary inland native forests, such as the black woodpecker (*Campephilus magellanicus*), have experienced a decline in their habitats, along with a decrease in the size and distribution range of their populations[51] (**Table 3**).

Different studies conducted in diverse ecosystems show that fragmentation and deforestation alter a set of variables related to forest structure; likewise, fragment size is significantly related to species composition and community structure[12,13,18,59,60]. Structural differences in vegetation have been associated with changes in bird composition between habitats in the "cordillera"[52,53] (**Table 3**), possibly responding to variables such as increased irradiance and temperature[61]. Likewise, it has been shown that the probability of site use by carnivores at risk of extinction, such as the guigna (*Leopardus guigna*), Darwin's fox and puma, increases as the structural diversity of the habitat increases[54] (**Table 3**).

Edge effects. In the present study, primary and secondary native forests exhibited a high contrast due to the interface between anthropogenic land uses and secondary native vegetation. Previous studies in Chile and southern Portugal report that eucalyptus (*Eucalyptus globulus* Labill) plantations present high contrast edges with the natural habitat due to their monospecific composition and simple structure[62,63], which can directly affect the movement of organisms[11]. In the "cordillera" populations of amphibians at risk of extinction, such as Vanzolini's spiny-breasted toad and Bullock's toad (*Telmatobufo bullocki*), have been found in small remnants of native forest surrounded by plantations of exotic species. These plantations affect the mobility of amphibians and the development of their life cycle[55,56] (**Table 3**). Likewise, erosion processes related to harvesting and forest plantation management generate bio- physical changes and sedimentation of water bodies associated with their habitat, eliminating suitable conditions for their reproduction[56] (**Table 3**).

Isolation effects between habitats. A discontinuous spatial pattern of habitats, such as the one described for the study area, can lead to a decrease in functional connectivity between suitable sites for species and to an alteration of dispersal capacity depending on the conditions of the matrix that separates them[10,59]. This in turn induces an increased risk of local extinctions by making species more vulnerable to stochastic processes, natural catastrophes, human threats and loss of genetic variability[8,10,64]. In this sense, it has been shown that populations of the tree species pitao (*P. punctata*) in the "cordillera", and of restricted distribution in the coastal mountain range in Chile, present low genetic variability within each locality, and a high degree of genetic differentiation between localities due to the effect of isolation between populations[57] (**Table 3**), compared to other tree species of south-central Chile, such as queuleyelhualo (*Lophozonia glauca*) Heenan and Smissen[65,66]. Accordingly, it can be inferred that *P. punctata* is in a genetic bottleneck, even more so if one considers that its area of occupancy is less than 1,000 ha and that less than 1,000 mature individuals persist in the wild[24].

The Nahuelbuta mountain range should be considered a premium conservation landscape, as it still concentrates high levels of biodiversity and endemism, but at the same time an advanced state of transformation and progressive fragmentation of native forests. This premium condition within the biodiversity hotspot justifies the urgency of safeguarding the different species of flora and fauna whose risk of extinction may increase due to the loss and modification of their habitats. This condition is also based on their low degree of protection (±10.4%), with 10 areas of high conservation value with an approximate surface area of 57,500 ha, with Caramávida Creek being the largest conservation area in the landscape (37,000 ha). The only two areas protected by the National System of State Protected Wildlife Areas are Nahuelbuta National Park (6,832 ha) and Contulmo Natural Monument (82 ha), whose size is difficult to sustain the area's high biodiversity[67,68].

We suggest the urgent implementation of strategies for conservation planning in the Nahuelbuta mountain range that involve: restoration of degraded ecosystems, connectivity of forest fragments in the landscape, conservation of threatened species in the landscape, updating of priority sites for biodiversity conservation, implementation of new protected areas, and analysis of the ecological impacts of habitat loss on species and communities of flora and fauna.

Finally, it is suggested that future research should address the causes of landscape transformation and the loss of native forest in the “cordillera”, in order to be included in actions for biodiversity conservation and territorial planning.

Conflict of interest

The authors declared no conflict of interest.

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