Informe

Identificación de refugios climáticos terrestres y marinos para la biodiversidad en la Patagonia chilena

Identification of terrestrial and marine climate refugia for biodiversity in Chilean Patagonia

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Programa Austral Patagonia
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Conocimiento y Naturaleza

Identification climate refugia for biodiversity in land and marine areas of the Chilean Patagonia to assess the overlapping of potential climate refugia with protected wild areas. The analysis seeks to determine areas of interest for conservation considering this new variable.

Austral Patagonia is a program under Universidad Austral de Chile **seeking to improve the conservation status of** land and marine ecosystems in the Chilean Patagonia.

Patagonia Austral Program

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1. INTRODUCTION

The identification of priority areas for biodiversity conservation is crucial to define new conservation areas and assess existing ones (Brooks *et al.*, 2006). This identification can be accomplished based on the definition of existing conservation targets within an area (species, ecosystems, processes), and/or by identifying ecosystems that act as climate refugia for biodiversity. In recent years, the identification of climate refugia has become a relevant tool for defining priority sites for biodiversity conservation, becoming critical in the systematic conservation planning process (Moilanen *et al.*, 2022). One example is conservation scientific studies and planning programs conducted in North America, particularly in the United States and Canada, which include definitions of climate refugia (Ramirez *et al.*, 2017; Halofsky *et al.*, 2022). Likewise, California's state and federal government agencies incorporated vegetation climate refugia maps for vertebrate species into reforestation planning following wildfires (Thorne *et al.*, 2020). This experience was useful to define a step-by-step conservation process that includes identifying management goals, mapping of climate refugia using physical and biological data, and selecting and implementing actions to protect identified climate refugia and ensure their maintenance over time through monitoring (Morelli *et al.* 2016).

Defining Climate Refugium

Overall, the concept of refugium corresponds to the state of being safe or protected from any danger or difficulty (Morelli *et al.*, 2020). From an ecological point of view, it can be understood as an area in which species and populations can survive for long time periods (Ashcroft *et al.*, 2010), or as geographical areas that, given their climatic conditions or topographic features, have allowed for the maintenance of species and populations for long time periods in different parts of the planet (Selwood *et al.* 2020). The best-known use of the refuge concept is related to the identification of glacial refugia during the Last Glacial Maximum (LGM), which allowed the existence of distinct evolutionary lineages and the persistence of the genetic diversity of certain species (examples in Villagran 1991; Mathiasen *et al.* 2020). Refugia, therefore, emerge as an important issue not only for ecology and biogeography, but also for biological conservation, since their identification and protection can ensure the subsistence of species under current and future climate conditions (Keppel *et al.*, 2012; Dai *et al.*, 2019).

Faced with the challenges imposed by the acceleration of climate change caused by human behavior and its impacts on ecosystems and biodiversity, the identification of biodiversity refugia has become increasingly important. For this reason, the original definition of glacial refugium has been extended to different time and spatial scales, and refugia are now understood not only as places related to former glacial areas, but also to areas with high environmental heterogeneity, i.e., with particular site conditions, including relief and soil (Thorne *et al.*, 2020). The concept of climate refugia emerges, then, to identify those areas that help mitigate climate change impacts and guarantee the persistence of species, communities, and ecosystems (Barrows *et al.*, 2020), favoring their adaptation to climate change impacts (Reside *et al.*, 2013). This being so, climate refugia are broadly defined as all those areas in the territory that provide a level of protection against current climate change impacts, and allow for the persistence of physical, ecological, or sociocultural resources (Morelli *et al.*, 2016; Barrows *et al.*, 2020). From an ecological point of view, these areas act as buffers against climate change impacts.

The distribution of climate refugia may differ from traditional protected areas (parks, reserves, sanctuaries, etc.), as the criteria that define them –for example, geodiversity and the rate of climate change– have not been considered in the definition of priority areas for global and regional scale protection (Stralberg, 2020a). Disclosing the spatial coverage mismatch between protected areas and climate refugia becomes critically relevant for ecosystems particularly sensitive to climate change, such as oceans. Climate change impacts have been identified even more explicitly in these ecosystems than on the land surface due to the greater sensitivity of some highly relevant elements, such as coral reefs. These, among many others, are dramatically accounting for the impact of rising sea temperatures (McWhorter *et al.* 2022). The identification of climate refugia in marine areas, therefore, becomes extremely relevant to prioritize protection areas that help establish conservation actions in specific areas, anticipating short- and medium-term impacts or threats. In addition, by applying joint approaches to the identification of climate refugia in terrestrial and marine environments, the interconnection occurring in the coastal environment can be explored, as these are among some of the most intervened areas by human action due to marine resource extraction and the advance in land use changes.

All that said, this study is a spatial determination exercise of climate refugia for the Chilean Patagonia –both terrestrial and marine– with a view to informing the identification of critical areas for conservation as well as climate change mitigation and/or adaptation policies. Identifying climate refugia in Patagonia is important since this Nature-Based Solution can be integrated into the Nationally Determined Contributions (NDCs), and/or into several regulations, including the Framework Climate Change Act, the National Climate Change Adaptation Plan (PNACC), the National Climate Change and Biodiversity Plan (PNACC-BIO), or under the law that will establish the new Biodiversity and Protected Areas Service (SBAP).

This work was carried out at the request of the Austral Patagonia Program of Universidad Austral de Chile, as part of its effort to provide relevant analysis and data to strengthen the protection system for the Chilean Patagonia's ecosystems. Similarly, this study is the follow-up of a recommendation made in the Austral Patagonia Program report (2020) "Patagonia Climate Refuge: Proposed nature-based solutions for national contributions before the United Nations Framework Convention on Climate Change" (Valencia *et al.*, 2020), as well as the recommendations made in the book *Conservación en la Patagonia chilena: evaluación del conocimiento, oportunidades y desafíos* (Castilla *et al.*, 2021).

About the Identification of Climate Refugia

The identification of climate refugia that represent environmental heterogeneity (Parks *et al.*, 2020) is addressed with digital elevation models that allow the characterization of the topography at different scales. When dealing with broad scales (over 1 sq. km), we speak of macro refugia, while at finer scales which allow for the mapping of complex topography areas, we speak of micro refugia (Stralberg *et al.*, 2020b). Both scales can be complementary, as they focus on the representation of different ecological processes. Therefore, their joint analysis can yield a more solid approach (Michalak *et al.*, 2020).

In turn, climate refugia should be understood as spatial and temporal gradients, and not as fixed and discrete points in space. Following this rationale, the climate refugium approach is most useful to curb climate change impacts by safeguarding spatially heterogeneous and dynamic areas (Michalak *et al.*, 2017; Michalak *et al.*, 2018). Similarly, if included in effective conservation actions, this approach would also allow for a sustainable delay of climate change impacts over time (Morelli *et al.*, 2020).

Knowing the relationship between protected areas and climate refugia would prove key in conservation planning, as the representation gaps of these refugia –within and outside protected areas– can determine the prioritization of short-term conservation actions to: 1) protect climate refugia that are outside the current protection systems; or 2) establish appropriate management plans for refugia that do match existing protected areas.

Study Goals

This work focuses on the hypothesis that climate refugia can complement and improve ecosystem representativeness within the Patagonia network protected areas, incorporating the spatial climate change dimension in their planning. The specific goals of this study are as follows:

1.-To identify terrestrial and marine climate refugia in Patagonia, combining biodiversity, geodiversity, and climate-related variables.

2.-To carry out a conservation gap analysis between the identified climate refugia and the network of marine and terrestrial protected areas.

2. METHODOLOGY

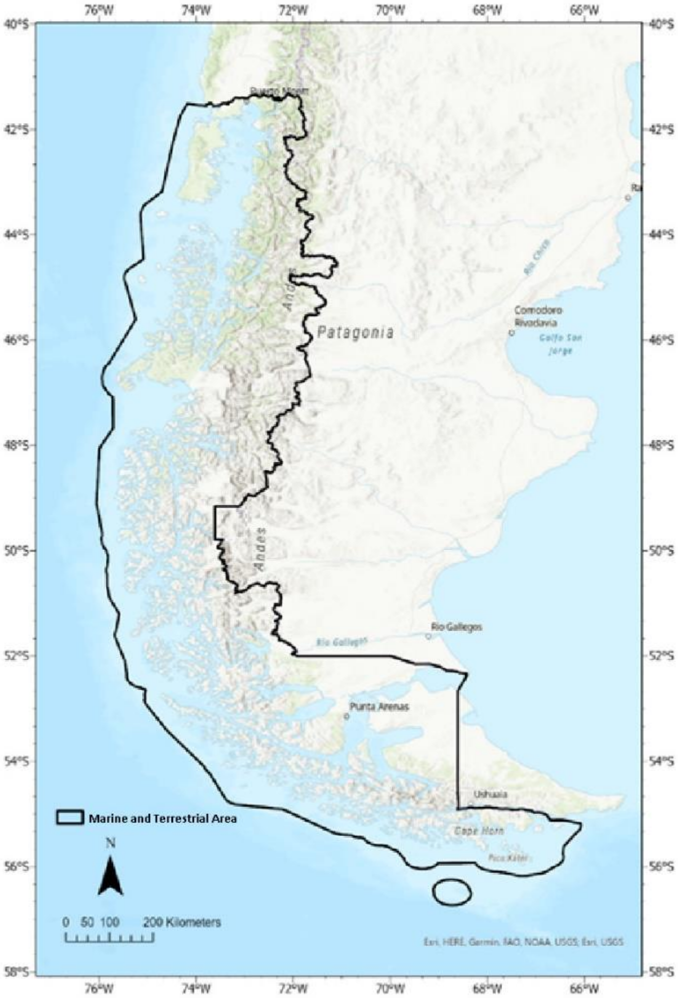
The present study used a climate refugium identification approach that introduces, at the terrestrial level, geodiversity elements (topographic position, heat load), climatic diversity, and spatial processes (climate change rate, biotic velocity). In the marine area, future changes in sea surface temperatures, primary productivity, and chlorophyll were considered as descriptors of areas with the greatest potential for maintaining species and community diversity.

In terms of their application as a biodiversity conservation planning tool, the climate refugia identified were evaluated according to their spatial correspondence with the state protected areas, as well as with the distribution of primary forests, in the terrestrial area, and macroalgae forests, in the marine area. This is because both primary forests and macroalgae forests are attributes that point to the pristine nature in the respective ecosystems.

2.1 Study Area

The study area was defined from 41° south latitude to 56° south latitude, corresponding to the terrestrial border of the Chilean Patagonia. The northern border of the terrestrial area studied is specifically defined by the borderlines of the Maullín, Puerto Montt, and Cochamó districts, in a longitudinal direction from the ocean to the mountain range. The marine area under study includes the marine ecoregion of Chiloé and the marine ecoregion of fjords and channels (Spalding *et al.*, 2007), considering a buffer area of 12 miles from the coastline (Figure 1).

Figure 1. Study area



2.2 Terrestrial Climate refugia

Terrestrial climate refugia were defined using three spatial criteria: geodiversity, rate of climate change, and biotic velocity, all of which were used in other studies to define climate refugia (Michalak *et al.*, 2020). Geodiversity (environmental diversity) was used by Carroll *et al.* (2017), as well as by Stralberg *et al.* (2018), although associated with two different climatic criteria: climate change rate velocity, in the case of Carroll *et al.* (2017); and biotic velocity in the case of Stralberg *et al.* (2018).

2.2.1 Geodiversity

Geodiversity –at Chile's continental level– is estimated by means of three diversity metrics: topographic, ecotypical, and climatic (Figure 2), following the method introduced by Carroll *et al.* (2017).

In this study, topographic diversity was calculated using the 90-meter SRTM v4.1 (Farr *et al.*, 2007) global elevation model (Farr *et al.*, 2007), transformed to the 100-meter scale through the resampling tool in ArcGis ArcMap, to simplify surface calculations. Elevation data from the SRTM model were converted to the heat load index (HLI) (McCune & Keon, 2002) and the topographic position index (TPI) (Stralberg *et al.*, 2020a). HLI is a metric based on slope, exposure, and latitude, and an estimate of the incident radiation potential that relates to landform diversity in a way that differs from elevation. TPI reflects the variability of the terrain, defining a gradient from areas with higher to lower slope. The diversity of both indices was calculated using the Shannon index between pairs of cells within a spatial neighborhood defined by moving windows, following the methodology described by Ackerly *et al.* (2010). The R rasterdiv package (Rocchini *et al.*, 2021) was used for the application of the Shannon index.

Ecotypic diversity is defined as a combination of bioclimatic variables, lithology, and land use types. This research considers the global classification of terrestrial ecological units developed by Sayre *et al.* (2014).

In addition, the calculation of a climate diversity metric was considered to have a complementary element to the prior variables that are based solely on land surface elements. For this purpose, the climate surfaces used were those generated for southern South America and presented in Pliscoff *et al.* (2014), whose data represent 19 bioclimatic variables obtained from monthly temperature and precipitation variables with a 1 km resolution for the 1950-2000 period. A principal component analysis was generated with the 19 bioclimatic variables to remove collinearity. To represent climatic diversity, the Shannon diversity index was calculated with the first component obtained from the previous analysis, using the same steps applied in the definition of topographic diversity. Finally, these geodiversity variables were rescaled in values from 0 to 1 and averaged to obtain a final layer.

2.2.2 Climate Change Velocity

The climate change velocity is the division between the temporal climate change rate (temperature and/or precipitation) and the climate variability rate in a spatial gradient (Loarie *et al.*, 2009). This calculation can be expressed from the present to the future (forward velocity) or from the future to present time (backward velocity) (Figure 3), the latter being the way to identify areas susceptible to be climate refugia (Carroll *et al.*, 2015).

For this analysis, the backward velocity of the annual mean temperature was calculated. The annual average temperature of climate surfaces was obtained from the Worldclim 2.1 dataset (http://worldclim.org) (Fink & Hijmans, 2017); the current temperature corresponds to the 1980-2010 period; the future temperature variable was selected from a global circulation model (HadGEM3-3GC31-LL) under a pessimistic projection scenario (SSP5 8.5) for the 2080-2100 period. The backward velocity calculation was made with the R vocc package (Garcia Molinos *et al.*, 2019).

2.2.3 Biotic Velocity

In addition, backward biotic velocity was calculated, following Carroll *et al.* (2015). This concept corresponds to the application of climate change velocity but using species distribution models as an element to define the spatial gradient. This analysis is performed using flora species distribution models, based on the models generated for all of Chile and presented in the article on Chile's Mediterranean flora (Fuentes-Castillo *et al.*, 2019). The spatial gradient was calculated using the current models, considering the future distribution scenario (for the 2070-2100 period) and the most pessimistic greenhouse gas emissions scenario RCP 8.5. The underlying assumption is that longer distances (higher values of retreat velocity) represent a greater potential to serve as a climate refugium. The calculation of backward biotic velocity used the same methodological approach as for measuring climate change velocity, using the R vocc package (García Molinos *et al.*, 2019). Finally, layers representing the spatial climate gradient and backward biotic velocity were selected to represent climate refugia (Figure 3).

2.2.4 Final Calculation of Terrestrial Climate Refugia

The identification of areas with the greatest capacity to be climate refugia in the Chilean Patagonia was carried out using a spatial prioritization approach with Zonation 5 software (Moilanen *et al.* 2022). This software is used worldwide to identify the sites that concentrate the highest value based on a set of elements expressed in geographic space. In this case, the layers corresponding to geodiversity, climate change velocity, and biotic velocity were combined (Figure 5) and, through a prioritization algorithm, the geographic areas that concentrate the greatest spatial coincidence of the values expressed in these layers were revealed.

In this study, Zonation's CAZMAX algorithm was used, and the three layers were given the same weight. Once the prioritized layer (spatial ranking) was obtained, the ranking was transformed to deciles, to identify the areas with the highest value as climate refugia. This ranking considers that the areas with the highest potential for climate refugia are those within the top 30 deciles, i.e. with more than a 70% probability, and are represented on a red scale for high potential and green for areas with low climate refugia potential.

2.2.5 Gap Analysis

As a final step, the layer of marine and terrestrial climate refugia was overlaid with the network of state protected wildlife areas (ASPE, by its acronym in Spanish). This was done to identify areas of high value as climate refugia that are not represented within this network, on the one hand, as well as those that are within an established protected area, on the other. For this gap analysis, 58 protected wilderness areas (ASPE)[1] corresponding to National Monuments, Nature Sanctuaries, National Reserves and National Parks in Chilean Patagonia, were considered.

In addition, an overlay of the primary forest layer was performed, using the database generated by Astorga *et al.* (2021), to identify matching areas between primary forest and areas with greater potential as climate refugia.

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[1] Áreas Silvestres Protegidas del Estado (ASPE) https://www.parquesnacionales.cl/que-es-el-snaspe/#1519269133272-d49c00bc-2e5a

Figure 2. Geodiversity calculation variables (topographic diversity)

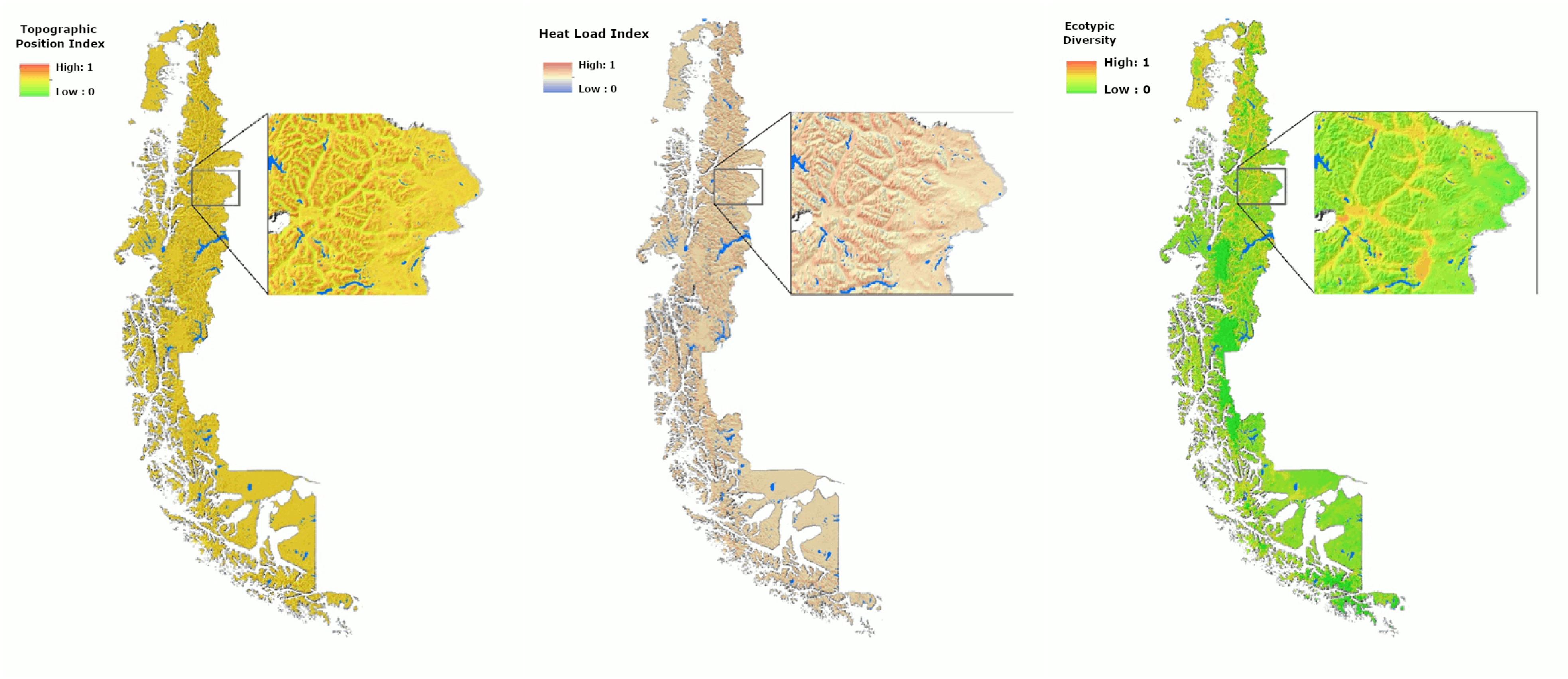
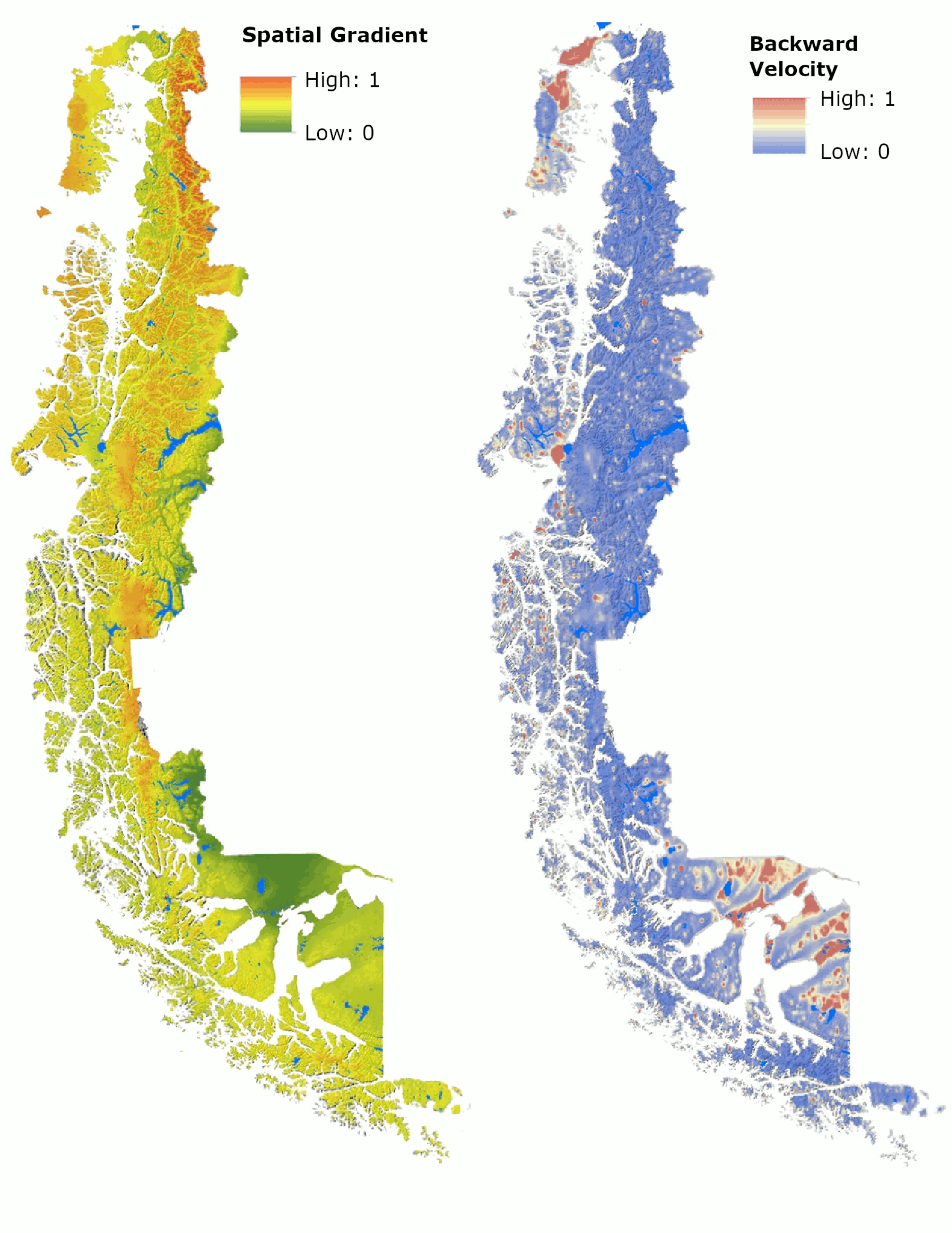


Figure 3. Variables defined to characterize biotic velocity (left-hand s) and climate change velocity (right-hand side)



2.2.6 Marine Climate Refugia

In the marine realm, areas of high value as climate refugia were identified based on the information available in the BIO-ORACLE database (Assis *et al.*, 2018), which has a spatial resolution of approximately 10 km. Current and future sea surface temperature, primary productivity, and chlorophyll layers were selected.

Areas with climate stability were identified by calculating the difference between the future and the current sea surface temperature layer. Lower values indicate greater future climate stability and, therefore, greater potential for climate refugia (Kyprioti *et al.*, 2021).

Once the future stability layer was obtained, the same spatial prioritization approach performed in the terrestrial domain was applied with the Zonation 5 software, combining three elements: Future climate stability, primary productivity, and chlorophyll (Figure 4). The variables and information sources are presented in Table 1. As in the terrestrial domain, once the prioritization ranking was obtained, the areas with the highest deciles were considered to correspond to climate refugia. These, in turn, were analyzed according to their correspondence with the marine protected areas (MPAs) network, including Marine Parks, Marine Reserves, Multiple-Use Coastal Areas and the sea portions of National Parks and National Reserves; and of macroalgae forests, according to the database presented by Mora-Soto *et al.* (2021) for the Patagonia fjords and channels.

Table 1. Variables and information sources used for the definition of terrestrial and marine climate refugia.

	Variable	**Source**
Terrestrial Climate Refugia		
Geodiversity	Topographic position	Elevation model
	Heat load	Elevation model
	Climatic diversity	Climatic surfaces (Pliscoff *et al.* 2014)
Climate change velocity	Current climatic surfaces	Climatic surfaces (Pliscoff *et al.* 2014)
	Future climatic surfaces	Climatic surfaces (Pliscoff *et al.* 2014)
Biotic velocity	Current distribution models	Fuentes-Castillo *et al.* 2019
	Future distribution models	Fuentes-Castillo *et al.* 2019
Marine Climate Refugia		
Climatic	Current surface temperature	BioOracle (Assis *et al.* 2018)
	Future surface temperature	BioOracle (Assis *et al.* 2018)
Biophysical	Chlorophyll	BioOracle (Assis *et al.* 2018)
	Primary productivity	BioOracle (Assis *et al.* 2018)

Figure 4. Marine refugia variables defined for patagonia

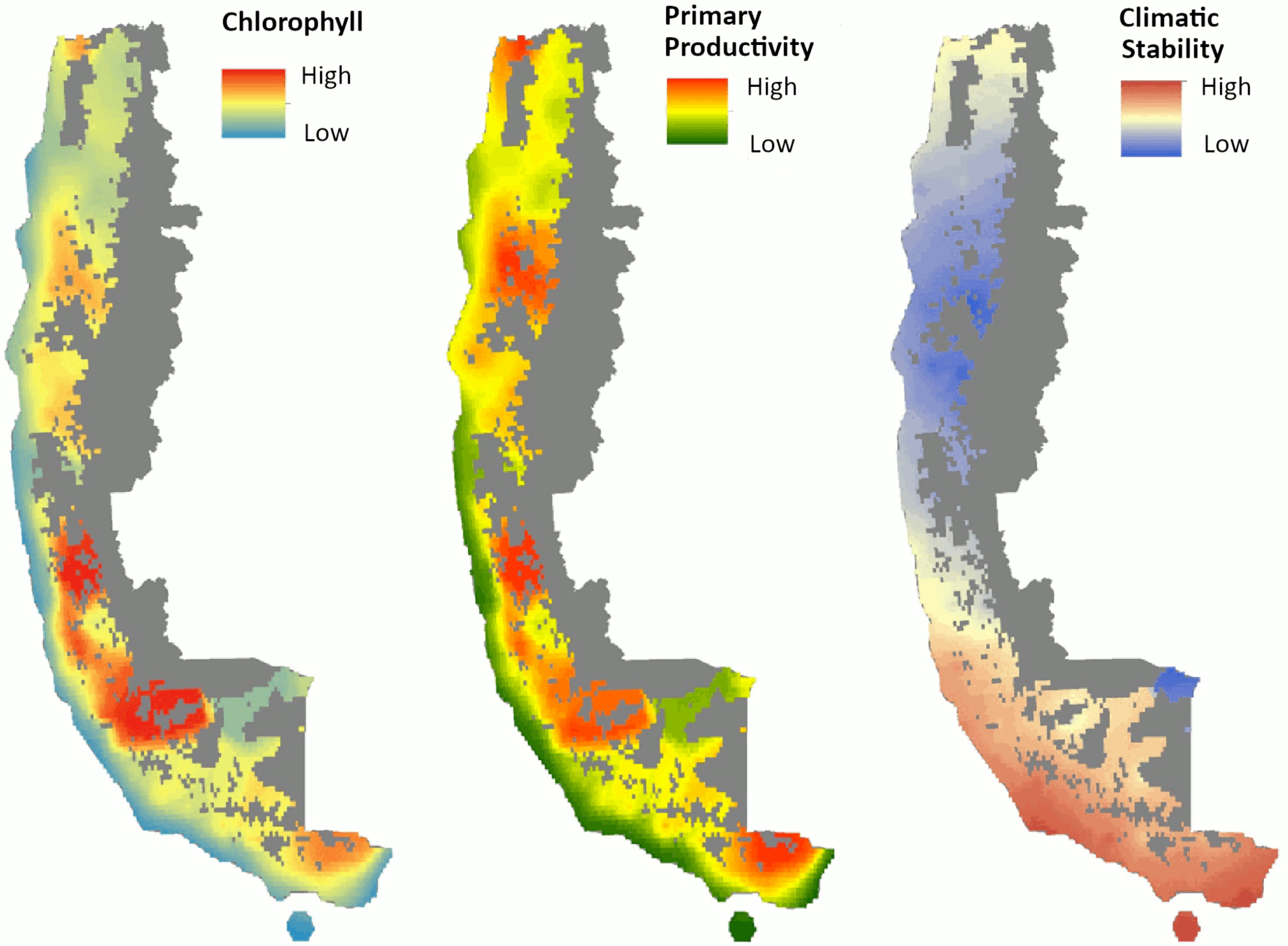
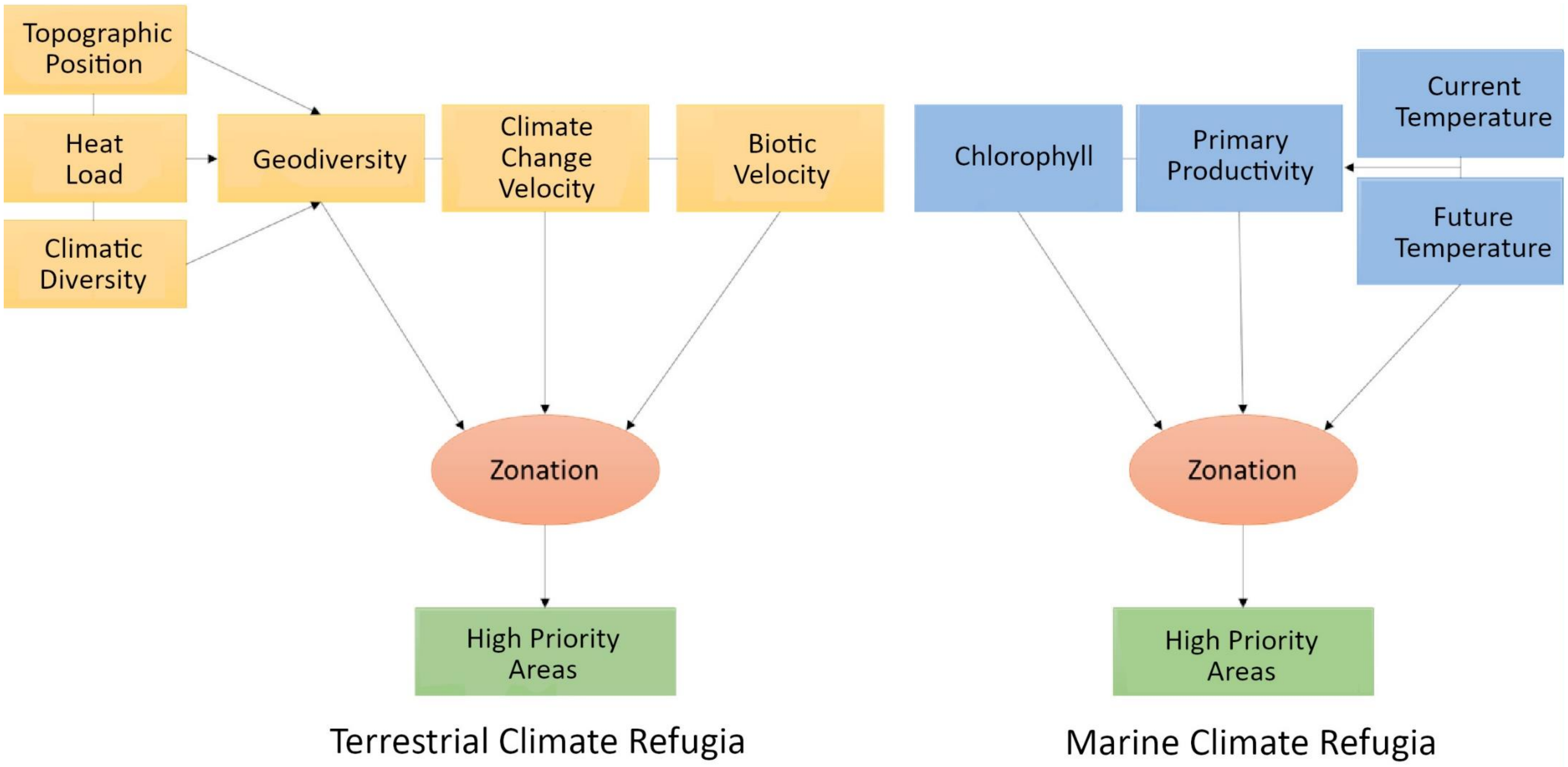


Figure 5. Methodological scheme for the identification of climate refugia



3. RESULTS

3.1 Terrestrial Climate Refugium

The combination of geodiversity, climate change velocity, and biotic velocity patterns (Figure 2) shows that the areas with the greatest climate refugium potential are distributed throughout Patagonia, but are concentrated in specific sectors: continental and insular Chiloé , in the Los Lagos Region; inland area between the coast and the eastern steppe zone, in the Aysén Region; and the southeastern continental tip and the northern zone of the Tierra del Fuego Island, in the Magallanes Region. In the latter region a smaller number of areas with climate refugium potential were identified.

Overlap with Protected Areas

An analysis of the overlap between climate refugia and terrestrial protected areas shows that the vast majority overlaps with areas of great refuge potential. Thus, 46 terrestrial protected areas –out of a total of 58 studied– have areas ranked within the top 30% of those with the greatest refuge potential. Of these 46, 21 have a sector ranked within the 10% highest refuge potential, i.e., areas with values between 90% and 100% of the total prioritization ranking. The units with the greatest climate refuge potential –in terms of maximum priority percentage– are Laguna de Los Cisnes Natural Monument, in Aysén; and Hornopirén National Park, Futaleufú National Reserve, and Lago Palena National Reserve, in the Los Lagos Region (Table 2). Notably, however, other protected wildlife areas have large surface areas with terrestrial climate refuge potential, including the following national parks: Bernardo O'Higgins, Laguna San Rafael, Pumalín, Katalalixar, and Guaitecas.

Overlap with Primary Forests

Primary forests in the Chilean Patagonia are spatially correlated with the areas identified as having the greatest climate refuge potential (Figures 6 and 7). Forty percent of the total primary forest area matches areas ranked within the 30% with the greatest refuge potential.

Figure 6. Presence of primary forests in the prioritization categories for the identification of climate refuges in Patagonia. Higher ranking means higher refuge potential.

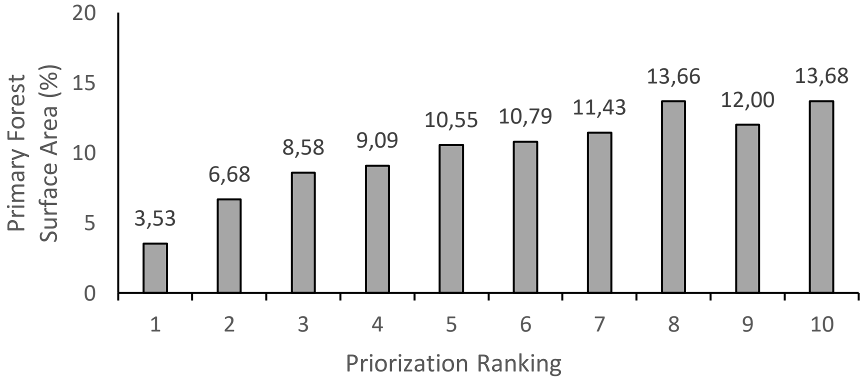
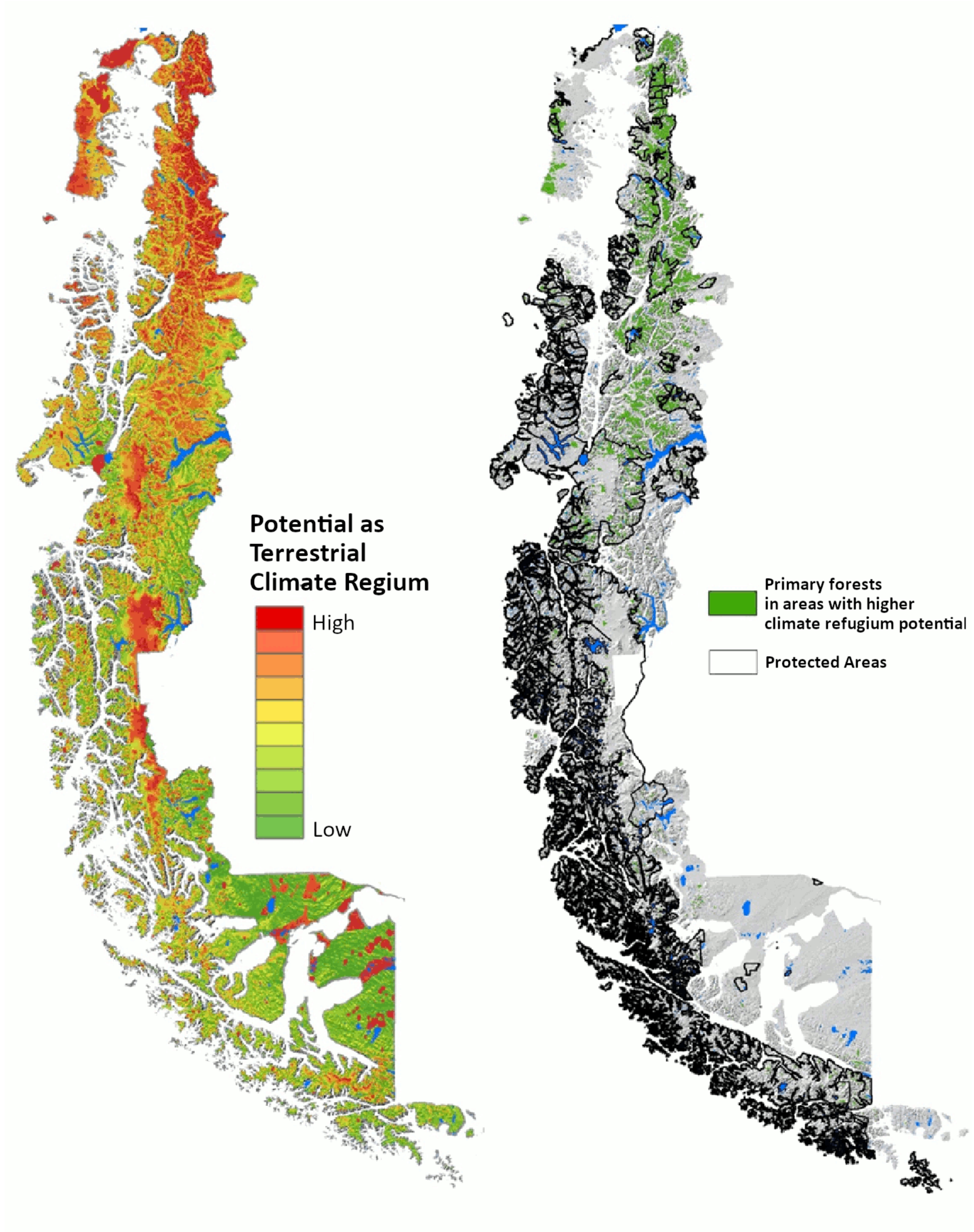


Table 2. Distribution in Patagonia's Terrestrial Protected Areas (National Parks, National Reserves, and Nature Sanctuaries). The areas identified as having the greatest climate refuge potential, the priority percentage, and the total surface of protected areas are indicated. The highest priority values per unit are in bold.

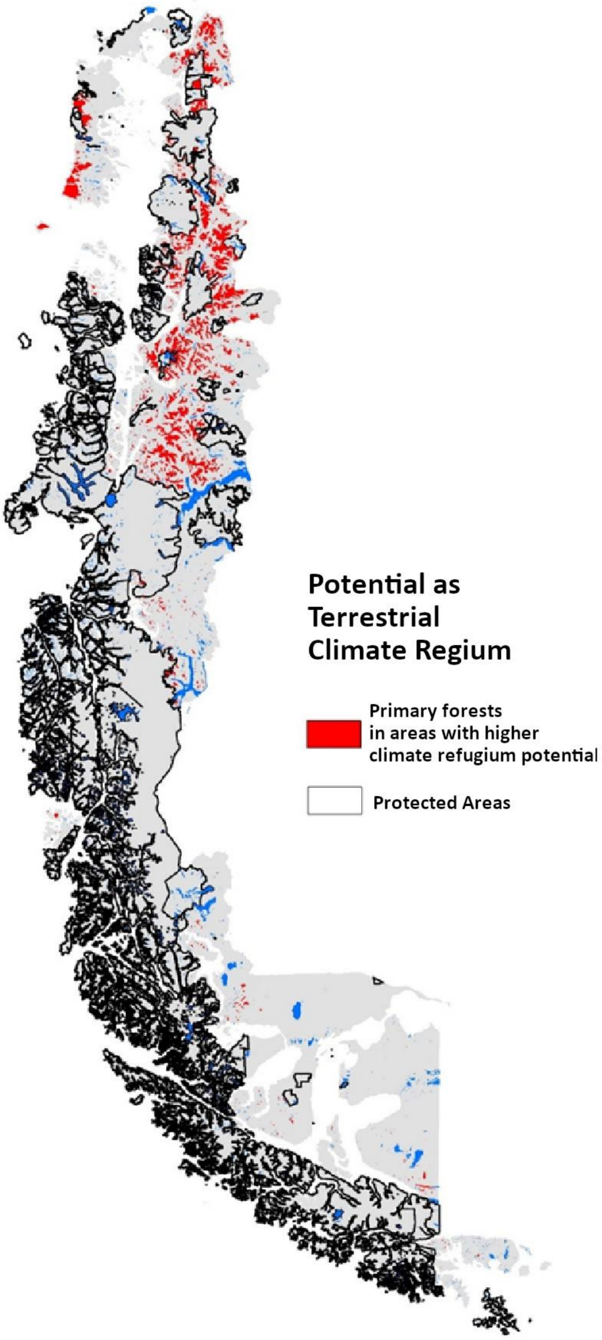
Protected Area	Maximum Priority Surface Area (ha)	Total Surface Area (ha)	Percentage of Maximum Priority
Alberto de Agostini National Park	26,547	1,457,748	1.82
Alerce Andino National Park	1,495	39,438	3.79
Bernardo O'Higgins	228,925	3,670,963	6.24
Cerro Castillo National Park	1,094	138,875	0.79
Chiloé National Park	11,202	41,892	26.74
Corvovado National Park	29,543	292,881	10.09
Hornopiren National Park	**28,625**	**48,357**	**59.19**
Isla Magdalena National Park	1,913	156,842	1.22
Kawesqar National Park	27,133	2,804,832	0.97
Laguna San Rafael National Park	141,141	1,709,211	8.26
Melimoyu National Park	3,459	82,949	4.17
Pali Aike National Park	222	5,155	4.30
Patagonia National Park	2,269	302,753	0.75
Pumalín Douglas Tompkins National Park	182,885	424,785	43.05
Queulat National Park	38,375	157,221	24.41
Torres del Paine National Park	7,518	228,449	3.29
Yendegaia National Park	2,222	153,659	1.45
Futaleufú National Reserve	**6,091**	**11,879**	**51.27**
Katalalixar National Reserve	34,570	727,340	4.75
Lago Cochrane National Reserve	497	7,434	6.68
Lago Jeinimeni National Reserve	711	159,927	0.44
Lago Las Torres National Reserve	1,652	17,032	9.70
Lago Palena National Reserve	**21,508**	**38,761**	**55.49**
Lago Rosselot National Reserve	1,002	12,334	8.12
Las Guaitecas National Reserve	25,293	1,079,223	2.34
Llanquihue National Reserve	1,845	33,986	5.43
Magallanes National Reserve	248	20,745	1.20
Río Simpson National Reserve	663	42,085	1.57
Laguna de los Cisnes Natural Monument	**2,263**	**3,089**	**73.27**
Turberas de Púlpito Nature's Sanctuary	79	244	32.56
Alerzales Potrero de Anay Nature's Sanctuary	3,004	6,224	48.26
Humedales de la Cuenca del Chepu Nature's Sanctuary	239	2,903	8.22
Humedales del Río Maullín Nature's Sanctuary	2,422	8,122	29.82

Figure 7. Distribution of terrestrial climate refugia (left-hand side) and primary forests in areas with high refuge potential (right-hand side).



When analyzing sites with climate refuge potential that are outside the network of protected wildlife areas (Figure 8), relevant areas emerge in the Los Lagos Region (continental Chiloé) and in the Aysén Region. A larger surface area with climate refuge potential is found in Dalcahue and Castro, in Chiloé; Cochamó, Futaleufú, and Palena in continental Chiloé; and the areas of Cisnes, Aysén, and Lago Verde in the Aysén Region. However, the latter have a much smaller surface area than what is found in the Los Lagos Region.

Figure 8. Distribution of areas with high terrestrial refuge potential within primary forests outside the protected wildlife areas' network



3.2 Marine Climate Refugia

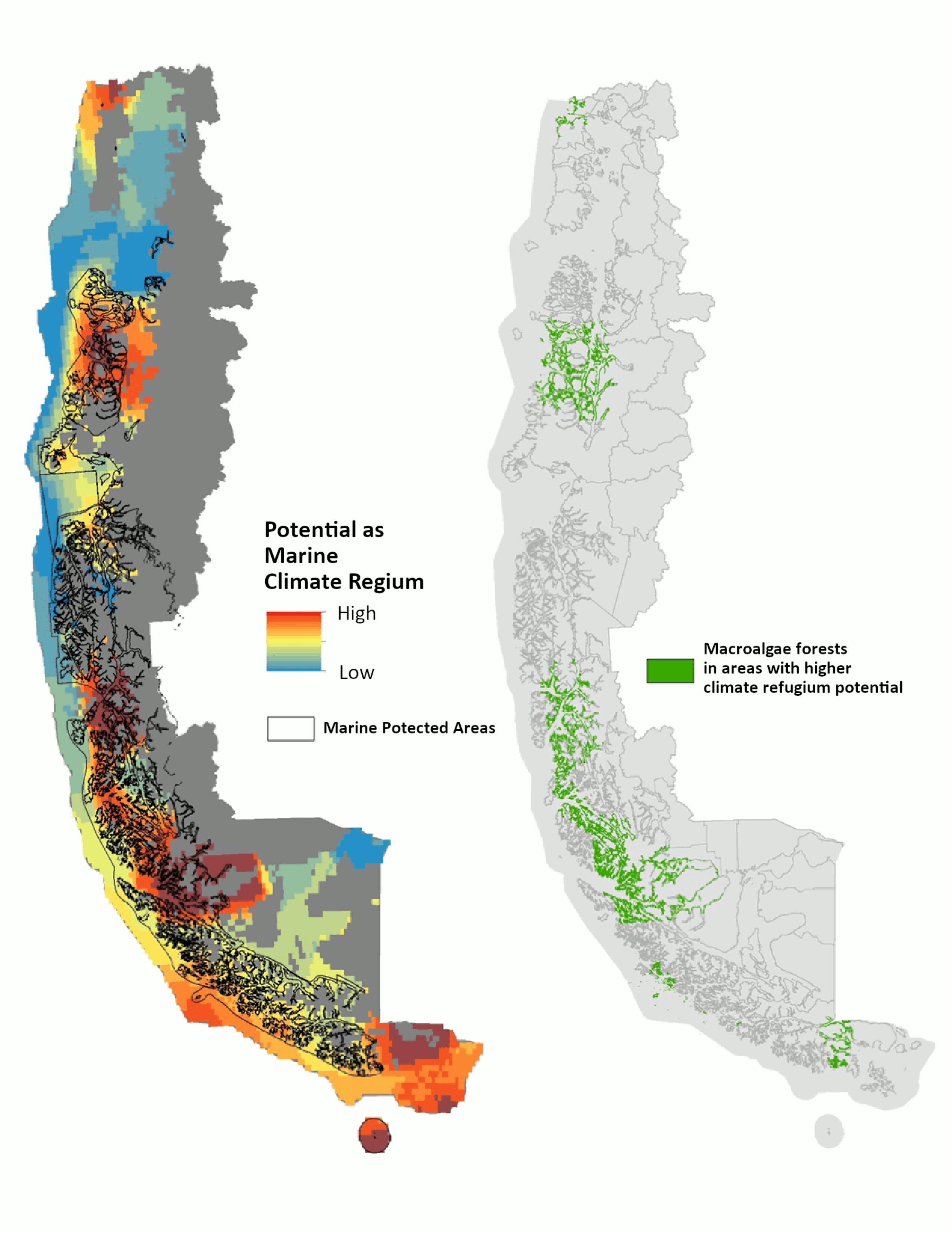
Marine climate refugia are distributed in five large zones within the marine area of the Chilean Patagonia (Figure 9). In the Los Lagos Region, a small marine climate refugium was identified in the north of the Isla Grande de Chiloé, the only one present in that region. In the Aysén Region, a second marine climate refugium was identified in the Guaitecas archipelago, which is also the only one in the region; while in the Magallanes Region, three areas with marine climate refuge potential were identified: one in the channels within the Bernardo O'Higgins National Park; a second one in the inland area of the Kawesqar National Reserve and around Riesco Island, and the third one around Navarino Island and the Diego Ramírez-Paso Drake Marine Park. Of these, the Pullinque Marine Reserve has the greatest refuge potential (Table 3). The areas with high refuge potential that do not overlap protected areas are only those of the northern zone of Chiloé and Navarino Island; however, both account for a small surface area.

Regarding the overlap of marine climate refugia with macroalgae forests, 27.9% of the areas with macroalgae forests match areas prioritized within the 30% of those with greatest marine climate refuges potential (Figure 8).

Table 3. Distribution of areas identified as having the greatest climate refuge potential within the marine protected areas of Patagonia (the highest surface area values per unit are in bold)

Protected Area	Maximum Priority Surface Area (ha)	Total Surface Area (ha)	Percentage of Maximum Priority
Francisco Coloane Costal Marine Protected Area	4,433	60,628	7.3
	1,126		1.9
Cabo de Hornos National Park	3,158	662,725	0.5
	68,152		10.3
	67,184		10.1
Pullinque Marie Reserve	21		2.7
	736	**756**	**97.3**
Alberto de Agostini National Park	126,077	1,117,521	11.3
	7,011		0.6
Bernardo O'Higgins National Park	25,380		3.2
	25,614		3.2
	100,887	**790,476**	**12.8**
Isla Magdalena National Park	5,045	44,398	11.4
Kawésqar National Reserve	353,737		13.5
	382,289		14.6
	402,383	**2,612,810**	**15.4**
Las Guaitecas National Reserve	161,742	**825,572**	19.6
	163,072		**19.8**
	96,118		11.6

Figure 9. Distribution of marine climate refugia (left-hand side) and macroalgae forests in areas with high refuge potential (right-hand side).



4. DISCUSSION

Based on the methodology presented and used in this study, both terrestrial and marine climate refugia can be spatially identified in the Chilean Patagonia.

The proposal to identify terrestrial climate refugia points to a combined index including geodiversity, climate change velocity, and biotic velocity, which turned out to be relevant factors for the characterization of terrestrial biodiversity. This formula was chosen because existing climate refugia exercises for Chile only considered the climatic dimension.

The case of marine climate refugia is different, with limitations acknowledged in terms of 1) the spatial resolutions available for climatic or biophysical surfaces, which lack a detail of less than 10 km; and 2) the biophysical variables used, which should introduce other variables to account for the biophysical diversity existing in the oceans. Moreover, the analysis failed to resort to variables associated with socio-environmental threats, a key dimension to apply to protected areas' planning; some of these threats could match areas identified as climate refugia and require specific conservation management.

This work introduces geodiversity through topographic diversity, and biodiversity through biotic velocity, which includes changes in the flora species richness patterns over time. The results show that –while there is no direct relationship between geodiversity and primary forests– the areas with the greatest climate refugia potential match the distribution of primary forests. This could be understood as a validation of the results and methodology proposed, since primary forests –by definition– have developed in areas with environmental heterogeneity and flora diversity. While biotic velocity, defined by the future and present difference in flora species richness, can be indirectly related to primary forests.

In addition, introducing the climate diversity variable provides a different dimension that spatially introduces climate change and proves that it can be integrated with the other criteria used to identify climate refugia. This is relevant since the use of different criteria are reflected in different spatial and temporal scales of analysis (concepts of micro and macro refugia), which can be presented in an integrated manner, as is the case in this work.

For the representation of climate refuges in the network of terrestrial protected areas in the Chilean Patagonia, it was determined that Laguna de Los Cisnes Natural Monument, in Aysén; and Hornopirén National Park, Futaleufú National Reserve, and Lake Palena National Reserve, in the Los Lagos Region, match refugia areas. However, it should be noted that in the northern zone of the Chilean Patagonia, areas with great climate refugium potential that do not overlap with protected areas were identified. This situation is much more evident in the southern zone, in the Magallanes Region, where climate refugia have been identified on Tierra del Fuego Island and within the Magellan steppe, which are not within any officially protected area.

In the case of marine climate refugia, despite the limitations mentioned above, areas that concentrate high primary productivity and that will remain more climatically stable in the future were identified. Therefore, these are areas with a high potential as climate refugia, although with a low total surface area. These sites correspond mainly to the Pullinque Marine Reserve, north of Chiloé, which is the area with the greatest potential, followed by Bernardo O'Higgins NP, Kawesqar NR, and Guaitecas NR, in the Magallanes Region.

Finally, the identification of climate refugia has two important implications for protected area planning in Patagonia. On the one hand, they provide a specific element to incorporate into management plans that, in many cases, are still under development in Patagonia. This is the issue for which the results presented here become crucial, as several potential refugia are identified within protected areas. On the other hand, and as inferences to this study, the sites identified as climate refugia outside protected areas should be considered complements to the existing protection network, valuing their complementarity and connectivity with the rest of the protected area network.

We are interested in highlighting the importance of identifying climate refugia in terrestrial, freshwater, or marine areas, as it serves as a tool for prioritizing resources within protected area planning. This is particularly important in the current scenario of lack of funding for protected areas.

5. CONCLUSION

- By using the climate refuge identification methodology, it was possible to survey areas with different climate refuge potential in Patagonia's terrestrial and marine areas.

- The representativeness of climate refugia in the protected areas is greater in the terrestrial part: 80% of the protected areas studied have areas with climate refuge potential.

- Terrestrial climate refugia are distributed throughout Patagonia, concentrating in the northern sector (insular and continental Chiloé), inland Aysén Region, and the northern zone of Tierra del Fuego Island in the Magallanes Region.

- Marine climate refugia are concentrated in four areas: the Pullinque Marine Reserve, north of Chiloé, which has the greatest potential; followed by Bernardo O'Higgins NP, Kawesqar NR, and Guaitecas NR in the Magallanes Region.

- It is important to note that terrestrial and marine climate refugia also have a high climate refuge potential, although with a low percentage of maximum priority, such as Bernardo O'Higgins NP, Laguna San Rafael NP, Pumalin NP, Katalalixar NR, Guaitecas NR on land; and Cabo de Hornos NP, and Alberto de Agostini NP in the marine area.

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