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Restoring riparian forests according to existing regulations could greatly improve connectivity for forest fauna in Chile

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ABSTRACT

Habitat connectivity is essential to facilitate species movement across fragmented landscapes, but hard to achieve at broad scales. The enforcement of existing land use policies could improve habitat connectivity, while providing legal support for implementation. Our goal was to evaluate how forest connectivity is affected if forests are restored according to existing riparian buffer regulations in Chile. We simulated forest restoration within 30 and 200 m of rivers in 99 large watersheds, following two sections of the forest regulation. We mapped habitat for two model forest species that have different minimum habitat sizes (15 and 30 ha), and for each we identified forest habitats and corridors using image morphology analysis. To quantify change in connectivity, we used a network graph index, the Relative Equivalent Connected Area. We found that both 30- and 200-m riparian buffers could have a positive effect on habitat connectivity. The 200-m buffers increased connectivity the most where forest cover was 20–40% (40% mean increase in connectivity index), while the 30-m buffers increased connectivity the most where forest cover was 40–60% (30% mean increase in connectivity index). The effect of riparian restoration scenarios was similar for both model species, suggesting that effective implementation of existing forest regulation could improve connectivity for fauna with a range of minimum habitat size requirements. Our findings also suggest that there is some flexibility in the buffer sizes that, if restored, would increase habitat connectivity. This flexibility could help ease the social and economic cost of implementing habitat restoration in productive lands.

1. Introduction

Habitat loss and fragmentation are the largest threats to biodiversity conservation (Haddad et al., 2015). Fragmentation can threaten species that are not adapted to patchy resources (Fahrig, 2007), and the probability of their extirpation is often high in small-and-isolated habitat patches (Haddad et al., 2015). Limited gene flow due to isolation stemming from fragmentation can cause a decline in genetic diversity (Cushman, McKelvey, Hayden, & Schwartz, 2006). Further, fragmentation can limit species ability to adapt to a changing climate (Knowlton & Graham, 2010). The degree to which the landscape facilitates or impedes movement of species to access resources and meet their life-cycle needs (Dunning, Danielson, & Pulliam, 1992) is referred to as habitat connectivity. The Convention on Biological Diversity (Convention on Biological Diversity, 2010) stated that "to reduce human pressure on biodiversity, fragmentation must be reduced and conservation areas must not only increase but also need to be well-connected." One of the largest conservation challenges today, then, is to identify where habitat connectivity can be protected or restored to help species to persist in human dominated landscapes.

Countries' existing laws and policy instruments can provide opportunities to protect and restore critical areas for connectivity (Lausche et al., 2013). One such policy is the maintenance of vegetation buffers along rivers. Vegetation riparian buffers are legally defined by different land administrations (Richardson, Naiman, & Bisson, 2012; Sweeney & Newbold, 2014), and they may or may not follow the extent and characteristics of the original riparian ecosystems, which usually extend from the edge of water bodies to the edge of upland vegetation (Naiman, Decamp, & McClain, 2005). Maintenance of riparian buffers has become one of the most common tools for protecting freshwater ecosystems from human activities (Richardson et al., 2012) as buffers can provide many of the ecological functions of the original riparian ecosystems. Riparian buffers maintain water quality by taking up nutrients, intercepting sediments, and improving bank stability (Sweeney & Newbold, 2014). Furthermore, buffers often contain some of the last remaining natural habitat in agricultural landscapes (González et al.,

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2017; Lovell & Sullivan, 2006), and thus can be extremely valuable for maintaining biodiversity (Bennett, Nimmo, & Radford, 2014). At broad scales, riparian buffers can contribute to forest connectivity, spanning watersheds, creating long-distance corridors, and maintaining habitat connectivity of distant protected areas (de la Fuente et al., 2018; Fremier et al., 2015; Jongman, Külvik, & Kristiansen, 2004).

Despite the conservation value of riparian forests and the fact that riparian buffers are essential instruments for protecting water quality, they are frequently deforested and degraded. There are often human activities in close proximity to rivers (Vörösmarty et al., 2010), which has resulted in substantial deforestation of riparian vegetation (Jones et al., 2010; Weissteiner et al., 2016). In addition, livestock grazing, selective logging, changes in river flow due to dam construction and colonization by invasive species alter the structure and composition of riparian vegetation (Capon, Chambers, Mac Nally, Naiman, & Williams, 2013). As riparian forests become smaller, disconnected from larger forest habitats, and degraded, their connectivity value for biodiversity is reduced (Clerici & Vogt, 2013; de la Fuente et al., 2018).

A promising approach to address these negative effects of ecosystem degradation is the restoration of riparian buffers in working landscapes (Jongman et al., 2004; Rey-Benayas et al., 2020). To be effective, riparian buffer restoration programs must meet ecological criteria that characterize the original vegetation and buffer minimum width rules to increase nutrients infiltration and reduce erosion (Rey-Benayas et al., 2020; Sweeney & Newbold, 2014). Buffer width size can affect the extent to which restored riparian buffers provide habitat connectivity as species responses to narrow habitats differ according to individual habitats and movement needs (Marczak et al., 2010). In temperate North America, riparian buffers of 30 m can reduce the effects of clear cuts on small mammal communities by maintaining similar richness in the 30-m buffer as in intact forests (Cockle & Richardson, 2003). The requirements are different for forest-interior birds that need riparian buffers > 100 m to maintain their population in logged forests (Shirley & Smith, 2005). In temperate South America, native riparian forest buffers of 25–50 m are used by understory birds for dispersal and as components of their territories (Sieving, Willson, & De Santo, 2000), while habitat generalist birds benefit from linear corridors of various widths to move between farm fields (Vergara, 2011). Overall wider buffers tend to provide habitat and connectivity between bigger patches for a larger numbers of species than narrower buffers, but wide buffers may interfere with owners' land use preferences (Lovell & Sullivan, 2006). There is general agreement among stakeholders that riparian buffers have a positive effect on the aesthetics and function of landscapes (Sullivan, Anderson, & Lovell, 2004). However, stakeholders differ in their support for establishing or expanding the width of riparian buffers, likely because doing so requires that some land currently in production be set aside for restoration (Sullivan et al., 2004). Therefore, understanding how narrow versus wide riparian buffers affect habitat connectivity could inform restoration programs that aim to balance habitat conservation with land use.

Defining countrywide conservation strategies to maintain functional habitat connectivity, the degree to which species can move across the landscape, is challenging because species' movement needs differ widely (Fahrig, 2007; Knowlton & Graham, 2010), and because methods to identify actual or functional connectivity are data- and resource-intensive (Beier, 2012). For example, a study to identify barriers to pronghorn (*Antilocapra americana*) migration routes took more than 5 years of data collection and a large budget for GPS collars and monitoring (Seidler, Long, Berger, Bergen, & Beckmann, 2014). Such studies are usually limited to a few charismatic species (e.g., Seidler et al., 2014; Tracy, Kantola, Baum, & Coulson, 2019). An alternative is to quantify structural habitat connectivity, the degree to which landscape elements are contiguous, combining existing knowledge of species autoecology from published studies and expert opinion as a proxy for empirical movement data to create maps of potential or structural habitat connectivity for habitat specialist species (Saura & Pascual-Hortal, 2007). By assuming that movement of habitat specialist species occurs mostly within suitable habitat, and not in matrix habitat, functional habitat connectivity can be simplified as a process that occurs within and among patches of habitat that are connected via corridors and linear strips of habitats (Saura, Vogt, Velázquez, Hernando, & Tejera, 2011). This assumption is well supported by scientific evidence that shows that linear corridors can enhance population stability, increase biodiversity and facilitate dispersal (Gilbert-Norton, Wilson, Stevens, & Beard, 2010; Resasco, 2019). In addition, this approach assumes that creating habitat connectivity for a habitat specialist will facilitate movement for other species as well (Breckheimer et al., 2014). This type of coarse analysis can be used to promote protection and restoration of critical habitats that secure species movements before they are lost to development and conservation is no longer economically and politically feasible (Lausche et al., 2013).

The goal of our study was to evaluate the effect of riparian forest restoration on landscape structural habitat connectivity for forest fauna, following riparian forest regulation guidelines of Chile. The Chilean government has committed to plant 500,000 ha of native forests to restore degraded land that alters water quality (Consejo de Política Forestal, 2016). We sought to inform this restoration effort by identifying where adding native forest along rivers would have the largest effects on habitat connectivity for forest wildlife. To meet our goal, we pursued the following three objectives:

1) to quantify forest gain if riparian forests were restored, using a narrow riparian restoration scenario (30 m) and a wide riparian restoration scenario (200 m),
2) to characterize the change in structural connectivity based on these hypothetical riparian restorations scenarios of 30-m and 200-m, and
3) to determine which width (30 m or 200 m) has the greatest effect on structural habitat connectivity for two model habitat specialist species with different minimum habitat size requirements.

2. Methods

2.1. Study area

We selected Chile for our study because of its topography, the fragmented distribution of its forest, and its existing policy dedicated to riparian forest protection (Fig. 1). First, the topography of Chile is characterized by four coarse longitudinal units, the coastline, the Coastal range, the Andean range, and, separating the two ranges, the middle valley of varying width (Errázuriz et al., 1998). This topographical profile is present in most of the largest watersheds, while many of the smallest watersheds are restricted to the coastal range (Errázuriz et al., 1998). Second, forest fragmentation is a concern in this hotspot of biodiversity (Echeverría et al., 2006), because deforestation is widespread in the middle valley, and large forests only remain in the Coastal and Andean ranges (Miranda et al., 2015). Last, deforestation of riparian forest is prevalent in all of Chile's biomes (Camus, 2006; Echeverría, Coomes, Hall, & Newton, 2008), despite the fact that, on paper, native forests next to natural watercourses are protected by past and current forest policy (Ministerio de Tierras y Colonización, 1931; Ministerio de Agricultura, 2008, 2011).

2.2. Forest law to design riparian forest restoration scenarios

We estimated the effects of narrow, 30-m riparian buffers for all permanent watercourses based on national guidelines established in the regulation to protect soil, water and wetlands (Ministerio de Agricultura, 2011; Table 1). This regulation establishes a variable protection zone next to watercourses, according to river size, river regime and land slope. Because of the scale of our hydrological map (1:250.000), we assumed that watercourses in our map have a cross section wider than 0.5 m^2 and permanent flow. Thus, watercourses in

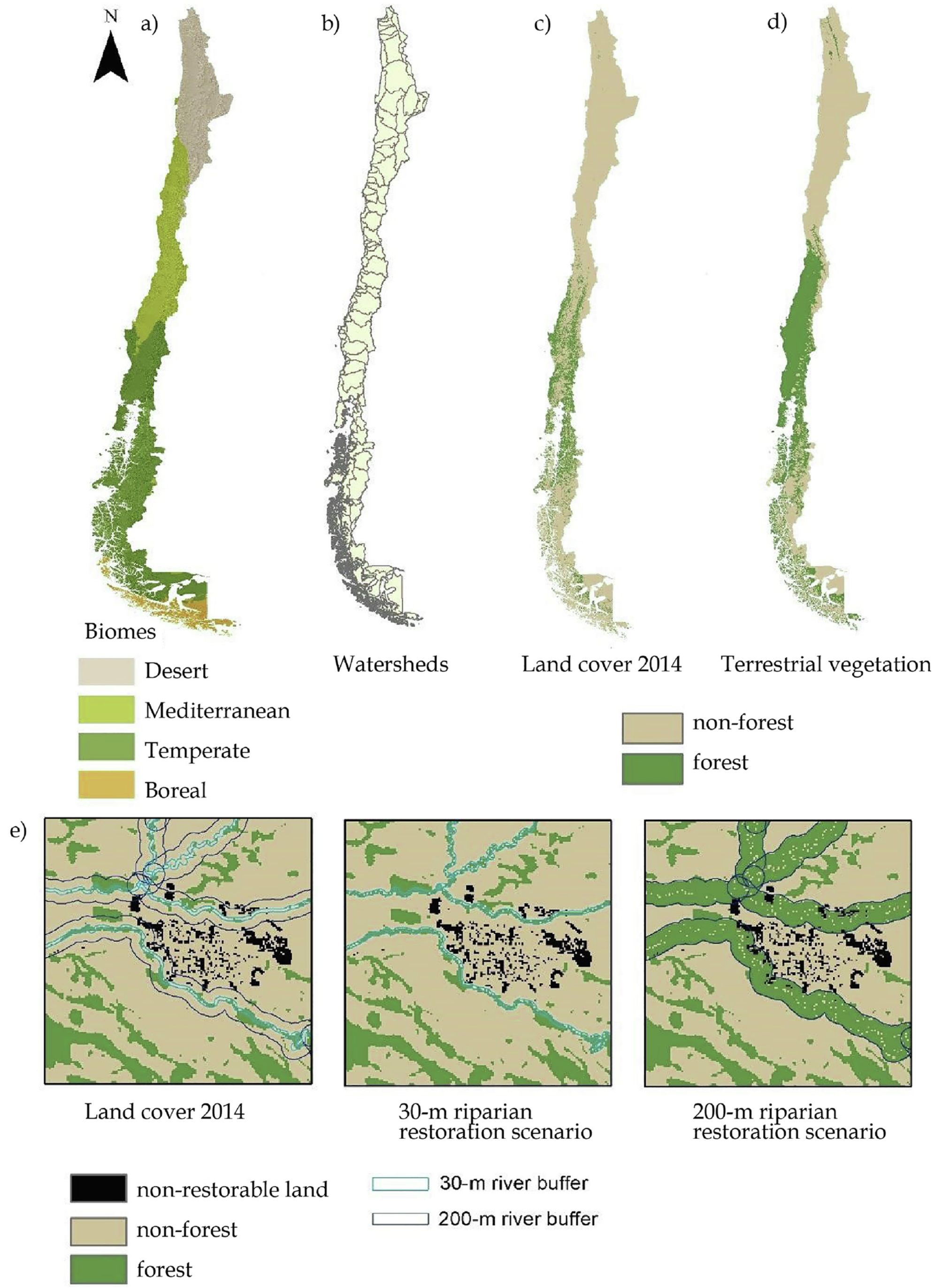

Fig. 1. Geographic information of Chile used in our analysis included a) biomes, b) watersheds, c) land-cover in 2014, including native forest and native and non-native forest plantations, and d) terrestrial vegetation dominated by trees. We built our restoration scenario using the e) hydrological network of the nation to construct a 30-m buffer and a 200-m buffer around rivers. We simulated forest restoration where potential for tree growth would sustain a forest community based on the terrestrial vegetation layer, and did not restore land cover with water, impervious surface, gravel, ice or snow.

our map are subject to 10-m to 30-m protection, depending on land slope. We used a 30-m fixed distance for our narrow buffer scenario across the study area to correspond directly with the 30-m resolution of our land cover map, and to simulate riparian guidance elsewhere that sets 30-m for protection of rivers (Sweeney & Newbold, 2014).

Second, we selected our wide 200-m riparian restoration scenario for all permanent watercourses using a different section of the forest law (Law to recover native forest and forestry development; Ministerio de Agricultura, 2008). Forest law defines “native forest for conservation and protection” as any forests within 200 m of natural watercourses that protect soil and water resources (Article 2, definition 5, forest law; Ministerio de Agricultura, 2011). Forests under this definition can be managed as long as silvicultural activities do not compromise the sustainability of the forest or alter forest biodiversity, soil, and quantity and quality of the water (Title III, Article 16; Ministerio de Agricultura, 2008, 2011). Our interpretation of this definition, then, is that native forest within 200 m of watercourses can be managed, but cannot be converted to other land use, such as agriculture.

2.3. Models of forest-specialist wildlife

To assess the effect of our restoration scenarios on species with a

Table 1
Chilean forest law that provide guidelines regarding riparian buffer protection.

Forest law	Flow regime	River size (m^2 cross section)	Slope	Buffer size	Reference
Native forest recovery and Forestry Law	Rule applies to permanent and intermittent regimes	Any	Any	200 m of sustainable management	(Ministerio de Agricultura 2008)
Soil, water and wetlands regulation	Rules apply to permanent and intermittent watercourse in northern and central Chile, and only to permanent watercourses in southern Chile	0 – 0,2		No protection	(Ministerio de Agricultura 2011)
		0,2 – 0,5		5 m	
		> 0,5	Slope < 30°	10 m	
		> 0,5	Slope 30° to 45°	20 m	
		> 0,5	Slope > 45°	30 m	

wide range of minimum habitat sizes, we used two model species that spend most of their time within forest cover. One species, the Black-throated Huet-huet, *Pteroptochos tarnii* (Rhynocryptidae), is a forest-understory specialist bird with a decreasing population trend (BirdLife International, 2018). Estimates of the species' minimum habitat size range from 7 to 10 ha (Castellón & Sieving, 2007). The species is rarely found outside of forest (Castellón & Sieving, 2007), and corridor facilitates the species movements and increases its ability to reach distant forest patches (Sieving et al., 2000). The other species, the Pudú, *Pudu puda* (Cervidae), is a small deer, classified as near threatened in the IUCN Red List (Silva-Rodríguez, Pastore, & Jiménez, 2016). Estimates of the territory size of Pudú in Chile are derived from a few collared individuals, and range from 16 to 26 ha (Jiménez, 2010). Pudú benefits from forest edges, where it can access areas with higher abundance of forbs and shrubs, their primary food, while remaining close to forest cover (Jiménez, 2010). These observations may explain why Pudús are often found along small remnants of native forest (Donoso, Grez, & Simonetti, 2003). Both of our model species can occupy many kinds of native forests, as well as forest plantation of non-native trees if these plantations have dense understory cover (Nájera & Simonetti, 2010; Silva-Rodríguez & Sieving, 2012), so we used native forest and native and non-native forest plantations as potential habitats to model structural connectivity.

2.4. Data layers

We combined three data layers in our analysis; a land cover map, the hydrological network, and a map of terrestrial vegetation, using ArcGIS® version 10.6 [ESRI 2018] as the mapping platform. We used a publicly available land cover map from year 2014 at 30-m resolution (Zhao et al. 2016; Fig. 1). We aggregated native forest and native and non-native forest plantation classes to create a forest/non-forest land cover map. Then, using a layer of the hydrological network of Chile (Ministerio de Bienes Nacionales, 2012), we created 30-m and 200-m buffers around natural watercourses, including permanent and intermittent rivers and creeks, following the forest law. To identify areas within each riparian buffer size capable of supporting forest, we used a geospatial layer of the terrestrial vegetation of Chile, available as a shape file (http://www.ide.cl/descargas/capas/MMA/PisosVegetacionalesPliscoff2017.zip). This map identifies 127 vegetation types, using bioclimatic information (Luebert & Pliscoff, 2006). Combining all vegetation types dominated by trees, we created a map of potential forest growth. We consider this map a reference of forest extent before the most intense deforestation occurred after European settlement.

2.5. Riparian restoration scenarios

To build our riparian restoration scenarios, we reclassified any areas with potential for forest growth that are classified as crops, pastures and shrubs in the 2014 land cover map. We did not reclassify forest, water, impervious surface, gravel, ice or snow. We quantified forest gain for each of the riparian forest restoration scenarios at the nation, biome and watershed level. To do so, we used a layer that delineates 99 watersheds of Chile (Ministerio de Obras Públicas, 1978) and a layer of the Nations' biomes (Luebert & Pliscoff, 2006). Then, we used the 99 watersheds as the study units in our subsequent connectivity analysis.

2.6. Habitat connectivity analysis

To determine the effect of our restoration scenarios on habitat connectivity for our two case study species, we modeled the structural connectivity of our landscapes using a network graph approach based on forest shape class, which we determined using image morphology analysis (Saura, Vogt et al., 2011). This combined approach is available in the software GUIDOS 2.8 (Vogt & Riitters, 2017).

1) Image morphology analysis: We classified forest into one of three shape classes; forest habitat, forest corridor, or small-and-isolated forest (Soille & Vogt, 2009). Using the concept of edge effect (*sensus* Ries, Fletcher, Battin, & Sisk, 2004) an area is classed as interior forest or edge forest depending on the definition of edge width. For example, if the edge width is set to 30 m, then a patch would have to be at least 90 × 90 m in size to contain a single pixel of interior habitat in its center. We defined two edge widths to approximate the minimum habitat thresholds for our two model species, and we defined areas as forest habitats if they contained at least some interior forest. However, because our land cover data had 30-m resolution, we could not map habitats of precisely 10 ha and 26 ha (the maximum estimated territory size for each species). Instead, we mapped habitats larger than ~15 ha and ~30 ha, using an edge width of 6 pixels for the Huet-huet (which means a forest needs to be at least 390 × 390 m in size to contain a single pixel of interior habitat) and 9 pixels for the Pudú (corresponding to a minimum of 570 × 570 m). Forests that were narrower than 390 m for the Huet-huet and narrower than 570 m for the Pudú, were classified as forest corridors if they were connected to forest habitats. Forests that did not meet the definition of forest habitats or corridors were classified as small-and-isolated forests. Then, to characterize the effect of the restoration scenario on the amount of forest classified as habitats and corridors, we summarized the percent of forest change in each of the three forest shape classes for the nation and by biome, including areas that were out of the species' current distributional range.
2) Network graph analysis: using the output from image morphology analysis, we built a network graph for each watershed with forest habitats as nodes and forest corridors as links (*sensus*, Saura, Estreguil, Mouton, & Rodríguez-Freire, 2011). We measured habitat connectivity of each network graph using the Equivalent Connected Area index (ECA) (Saura, Estreguil et al., 2011; Saura, Vogt et al., 2011; Saura & Pascual-Hortal, 2007). The Equivalent Connected Area index is the size (areal extent) of a single patch that would provide the same amount of connectivity as is observed in a

landscape pattern (i.e. the forest habitats and corridors) of interest (Saura, Estreguil et al., 2011). The formulation is as follow:

$$ECA = \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i a_j P_{ij}}$$

For a landscape with n number of forest habitat patches, a is the areal extent of a forest habitat patch. When $i \neq j$, a_i is the area of patch i and a_j is the area of patch j. P is the probability of connectivity between the two patches. In our network graph, $P_{ij} = 1$ when the two patches are connected with a corridor (link), and $P_{ij} = 0$ otherwise. When $i = j$, i and j are same patch, and $P_{ij} = 1$. Therefore, the ECA takes into account the connected area that exists within a forest habitat patch. For any given landscape, then, the Equivalent Connected Area index increases if i) the size of a forest habitat patch increases, ii) a new forest habitat patch is created, or iii) a new forest corridor is created between habitats patches that were previously isolated (Saura, Estreguil et al., 2011). Our restoration scenarios could result in an increase in connectivity for any of these three reasons. Because forest is the preferred habitat type of our model species, we assumed that species movements occurred within each of the forest habitats and among forest habitats connected with forest corridors, regardless of the corridor length. We opted to not limit connectivity using a distance threshold because movement distances vary widely among species, within species and within individuals at different life stages. Further, setting distance thresholds based on territory size can bias estimates of habitat connectivity (Blazquez-Cabrera et al., 2016). For instance, estimates of territory size for Pudú vary from 16 to 26 ha, while a single movement event (presumed to be dispersal) may be more than 20 km (Jiménez, 2010).

The Relative Equivalent Connected Area, which is the ECA divided by the total amount of forest habitat in each landscape, allows the comparison of habitat connectivity among landscapes of different sizes and amounts of forest (Saura, Estreguil et al., 2011; Saura, Vogt et al., 2011). We used this relative metric in all of our analysis. We also calculated Equivalent Connected Area relative to the size of each watershed to quantify the effect of restoration scenarios in adding to the areal extent of forest in each watershed.

To determine the effect of the hypothetical riparian restoration on habitat connectivity across watersheds with a wide range of sizes and forest amount, we calculated the change in the two Relative Equivalent Connected Area indices based on the 2014 land cover after the 30-m and 200-m restoration scenarios. We used maps to show variation in the connectivity metric among the nation's watersheds and within our model species' ranges of distribution (IUCN, http://www.iucnredlist.org). Using descriptive statistics (median and quantiles), we summarized these results along a gradient of percent forest ranges [0%–20% forest (n = 61), 20%–40% forest (n = 8), 40%–60% forest (n = 12), 60%–80% forest (n = 15) and > 80% (n = 3)]. We used R Studio (2019) to prepare summaries and graphs.

3. Results

The map of the 2014 land cover of Chile had 13.5 million ha of forested land, 11.3 million ha were native forests and 2.2 million ha were forest plantations. Forest amount increased by 2% and 15% under the 30- and 200-m buffer scenarios, approximately 0.3 and 2 million ha of forest respectively. Forest gain was widely distributed across watersheds of various biomes but, of course, forest gain was limited where there was no potential for tree growth (Fig. 2).

Our image morphology analysis revealed that the restoration scenarios greatly affected the amount of forest corridors and of small-and-isolated forests (Table 2). The land cover in 2014 based on Black-throated Huet-huet's minimum habitat size requirement had 8.4 million ha of forest habitat (~60% of the forest). Our 30- and 200-m restoration scenarios resulted in a 9% and 51% percentage point increase in corridors, and a 3% and 21% decrease in small-and-isolated forests, respectively. The 2014 land cover map using Pudú's minimum habitat size requirements had 6.9 million hectares of forest habitat (~52% of the forest). For this model species, the 30-m and 200-m restoration scenarios resulted in 9% and 47% percentage point increases in corridors, and in 6% and 16% decreases in small-and-isolated forests, respectively. While the general pattern of higher increases in corridors than forest habitat was consistent across the nation, it varied among biomes. For example, in the Mediterranean region, our 200-m scenario had a large effect on the amount of forest habitat on landscapes modeled using the Black-throated Huet-huet minimum habitat requirements, expanding forest habitat larger than 15 ha by 25% percentage point (Fig. 3).

When assessing habitat connectivity within the range of distribution of our model species, we found that forest habitat in the 2014 land cover map was well connected for both species, but varied widely among watersheds (Fig. 4). The Relative Equivalent Connected Area was on average 70% (SD = 25.69%; range: 20%–100%; n = 29 watersheds) for the Black-throated Huet-huet and 83.44% (SD = 18.11%; range: 50%–100%; n = 25 watersheds) for the Pudú. Similarly, the effect of the restoration scenarios on the Relative Equivalent Connected Area also varied widely among watersheds. For the Black-throated Huet-huet, the 30-m and 200-m scenario increases in percentage points ranged from 0% to 40%, a 10.97% ± 15.32% and 13.24% ± 15.11% mean and standard deviation increase in percentage points, respectively. For the Pudú, the 30-m and 200-m scenario increases in percentage point ranged from 0% to 39%, a 8.16% ± 14.46% and 9.76% ± 14.18% mean and standard deviation increase in percentage points, respectively.

The effect of the two restoration scenarios in adding total area of habitat for the two species was small when we compared it to the sizes of watersheds. For the Black-Throated Huet-huet in the 2014 land cover map, the amount of Equivalent Connected Area relative to the size of the watershed was on average 18.35% (SD = 17.20%, range: 0%-64.72%, n = 29), and increased very little under our 30-m and 200-m riparian restoration scenarios (1.95% ± 3.11% and 4.60% ± 3.86% mean and standard deviation increase in percentage point, respectively). Our results were similar for the Pudú, a species with a larger minimum habitat size requirement. For this species, the 2014 land cover map had an Equivalent Connected Area relative to the size of the watershed that ranged from 0% to 54.31% (mean = 17.55%, SD = 13.36%, n = 25). However, the restoration scenario resulted in a larger increase in the Equivalent Connected Area relative to the size of the watershed for the Pudú, approximately 10% percentage points for the 30-m (mean = 8.11%, SD = 3.84%, range: 1%-15.71%) and 10% percentage points for 200-m scenario (mean = 9.76%, SD = 4.73%, range: 1%–19%).

Simulated riparian restoration increased habitat connectivity the most for both modeled species in landscapes with an intermediate amount of forest (20%-60%; Fig. 5). The effect of the riparian restoration scenarios varied widely for watersheds with < 20% of forest. The 200-m riparian restoration increased habitat connectivity the most in watersheds with 20% to 40% of forest, with a median increase of 31% and 29% percentage points of Relative Equivalent Connected Area for our model landscape base on minimum habitat for the Black-throated Huet-huet and Pudú, respectively. Our 30-m riparian restoration scenario increased habitat connectivity the most in watersheds with 40% to 60% of forest, where there was a median increase of 44% and 41% percentage points of Relative Equivalent Connected Area for our model landscapes based on minimum habitat for Black-throated Huet-huet and Pudú, respectively. In watersheds with more than 60% of forest, restoring riparian forest had a marginal change in the relative amount of connected habitat.

4. Discussion

Our goal was to assess the effect of riparian forest restoration on structural habitat connectivity of forest specialist fauna at broad scales,

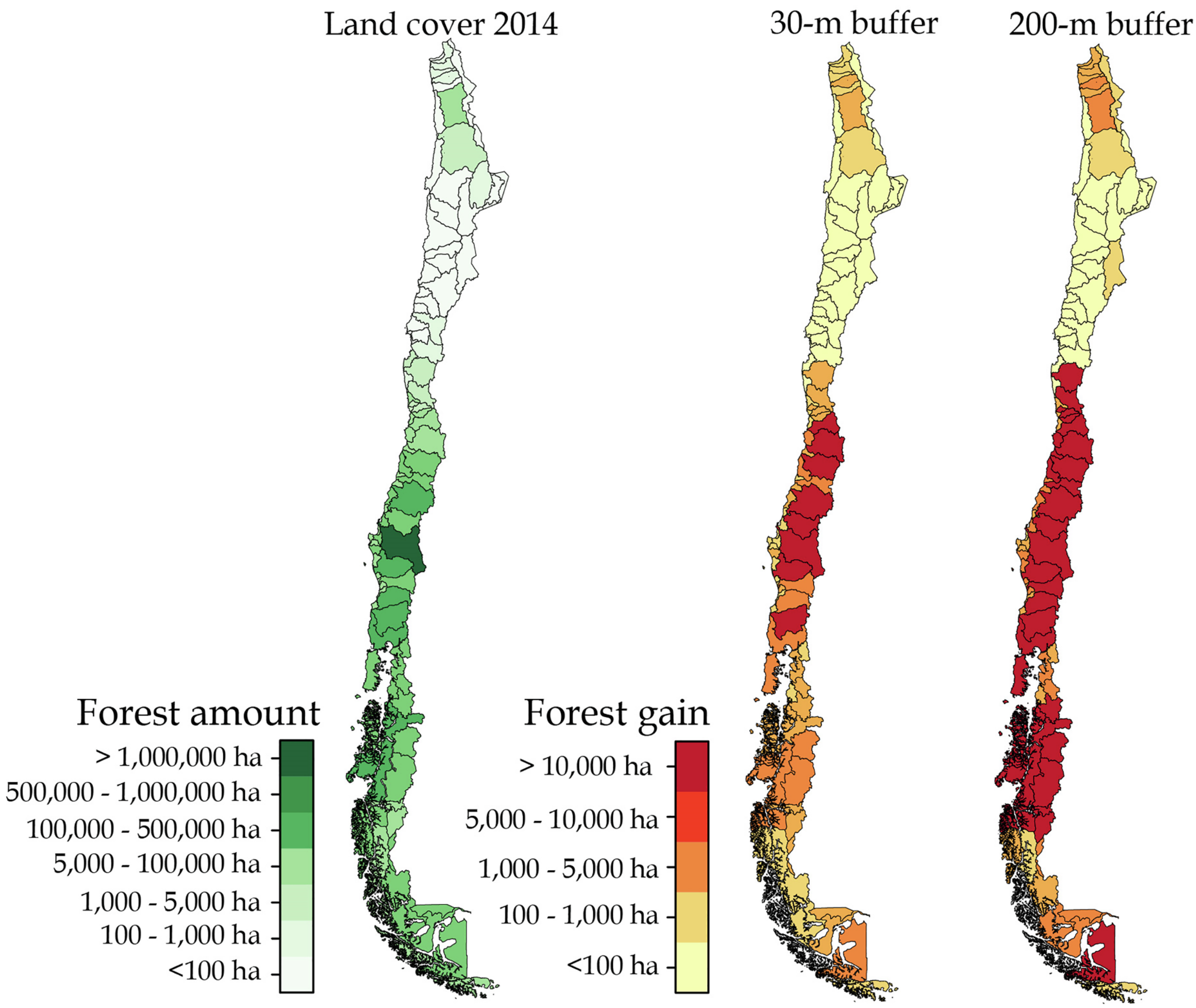

Fig. 2. Forest amount in the land cover 2014 map (left), and forest gain with the riparian restoration scenario (right) of 30-m and 200-m buffer for 99 watersheds. The 30-m riparian restoration scenario increased the forest amount by ~300,000 ha and the 200-m riparian restoration scenario increased forest amount by ~2 M ha. Light color indicate watersheds with smallest amount of forest in the land cover 2014 map (green gradient), and with the smallest forest gain in the case of the scenarios (red gradient). Darker colors indicate maximum forest amount in the land cover 2014 map and largest gain in forest in the restoration scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in accordance with existing forest regulation. The Chilean government has committed to plant 500,000 ha of forest to restore degraded land, and improve carbon stocks and water quality (Consejo de Política Forestal, 2016). Our network graph analysis based on the Equivalent Connected Area index showed where locating these restoration efforts along rivers can most improve landscape structural habitat connectivity for forest fauna. Where forest cover is less than 40% of the landscape, such as several watersheds in the Mediterranean biome, restoration of 200-m riparian buffers will provide the largest increase in habitat connectivity. Where forest cover ranges from 40% to 60% of the landscape, such as many of the watersheds in the Temperate biome, restoration of 30-m riparian buffers will suffice to increased habitat connectivity. These results showed buffers with a wide range of sizes, from 30 to 200 m, can increase forest structural connectivity. Wide corridors are frequently preferred as a conservation strategy to create connected habitats (Gilbert-Norton et al., 2010; Resasco, 2019), because they provide better habitat for more forest species than narrow corridors (Shirley & Smith, 2005), and reduce the proportion of forest exposed to edge (Ries et al., 2004). However, economic and social costs limit opportunities to create wide corridors (Sullivan et al., 2004). Therefore, buffer size prescriptions that are more flexible and that can be adapted to local conditions may facilitate implementation and social acceptance of conservation plans, especially in agricultural areas where restoration is often needed (Clerici & Vogt, 2013; de la Fuente et al., 2018; Rey-Benayas et al., 2020).

Our restoration scenarios along rivers increased habitat connectivity similarly for two species with quite different minimum habitat requirements. We infer from this result that species with a wide variety of minimum habitat size requirements would also benefit from increasing connectivity using riparian forest corridors. For example, the small güiña cat (*Leopardus guigna*), with home range larger than 100 ha, can persist in agricultural areas where little habitat remains (Gálvez et al., 2018), but makes use of riparian corridors to access remaining habitats (Schüttler et al., 2017). Like the güiña cat, many other forest generalist species use corridors for movement, especially riparian corridors (Sieving et al., 2000; Vergara, 2011). Our results suggest that restoration along rivers can conserve habitat that would allow movement for these species in Chile. This is advantageous when planning for conservation because information about minimum habitat size requirements is scarce for the vast majority of species.

Our results further showed that riparian forest restoration could increase long-distance habitat connectivity. In some of the watersheds we studied, riparian forest restoration resulted in corridors that were long enough to connect forests located in distant mountain ranges, and

Table 2
Summary shows nation and biomes total amount of forest and forest classified in three shapes, habitat, corridor and small-and-isolated forest for the land cover in 2014 and after 30-m and 200-m riparian restoration scenarios. Change is shown in hectares and percent change.

	Black-throated Huet-huet (> 15 ha minimum habitat)					Pudú (> 30 ha minimum habitat)				
		Change in hectares		Percent change			Change in hectares		Percent change	
	Land cover 2014	30-m	200-m	30-m	200-m	Land cover 2014	30-m	200-m	30-m	200-m
Nation										
Forest	13,283,423	308,225	2,026,956	2	15	13,283,423	308,225	2,026,956	2	15
Forest habitats	8,445,874	32,421	616,042	0	7	6,863,378	32,534	253,888	0	4
Forest corridor	3,366,792	316,900	1,722,454	9	51	4,442,044	387,461	2,089,266	9	47
Small-and- isolated forest	1,470,778	−41,117	−311,561	−3	−21	1,978,022	−111,791	−316,219	−6	−16
Desert										
Forest	24,208	5,725	29,357	24	121	24,208	5,725	29,357	24	121
Forest habitats	6,213	6	3,423	0	55	2,849	3	373	0	13
Forest corridor	9,651	185	7,495	2	78	10,233	166	1,786	2	17
Small-and- isolated forest	8,365	5,514	18,418	66	220	11,146	5,536	27,178	50	244
Mediterranean										
Forest	2,067,478	138,423	943,968	7	46	2,067,478	138,423	943,968	7	46
Forest habitats	1,193,118	5,370	299,768	0	25	925,235	4,606	68,249	0	7
Forest corridor	556,874	113,745	777,540	20	140	728,603	126,025	982,757	17	135
Small-and- isolated forest	317,486	19,308	−133,340	6	−42	413,639	7,793	−107,036	2	−26
Temperate										
Forest	10,755,345	158,328	1,020,085	1	9	10,755,345	158,328	1,020,085	1	9
Forest habitats	7,132,397	27,065	298,266	0	4	5,881,877	27,929	183,485	0	3
Forest corridor	2,633,987	195,321	911,316	7	35	3,534,788	251,126	1,063,517	7	30
Small-and- isolated forest	988,960	−64,057	−189,496	−6	−19	1,338,680	−120,727	−226,916	−9	−17
Boreal										
Forest	436,393	5,749	33,545	1	8	436,393	5,749	33,545	1	8
Forest habitats	114,147	−20	14,584	0	13	53,416	−2	1,782	0	3
Forest corridor	166,280	7,649	26,104	5	16	168,421	10,143	41,206	6	24
Small-and- isolated forest	155,966	−1,880	−7,142	−1	−5	214,556	−4,392	−9,443	−2	−4

across elevation gradients. Increasing access to habitat across all elevations would facilitate species movement during extreme weather events or in response to climate change (Krosby, Theobald, Norheim, & McRae, 2018). Our approach, though developed using the morphology of the hydrological system of Chile, could also be useful to plan for habitat connectivity in landscapes with similar topographies, such as the west coast of North America, Central America, the Caucasus Mountains, the Pyrenees, the Iberian Peninsula, and other landscapes where policies to maintain natural vegetation along rivers exist (Jongman et al., 2004).

We chose to model habitat connectivity for our specialist species assuming that plantations of non-native trees provide habitat for movement (Nájera & Simonetti, 2010; Silva-Rodríguez & Sieving, 2012). However, in order to provide habitat that meets species habitat requirements for reproduction and/or survival, these novel habitats must possess specific features that resemble species' native habitats. One such feature is a complex and diverse understory. In our study area, native forests have a well develop understory, frequently dominated by bamboo shrubs that provide essential habitat for a variety of species (Ibarra et al., 2018). Forest plantation of *Pinus* and *Eucalyptus* that lack a well develop understory are less likely to be occupied by forest specialist wildlife species (Nájera & Simonetti, 2010; Moreira-Arce et al., 2016). Furthermore, native terrestrial vegetation supports more biodiversity and provide more ecological functions than alternative novel ecosystems, and should be the end goal of ecological restoration (Gann et al., 2019). There is a diversity of riparian ecosystems in our study region of which more than a dozen are dominated by trees (Luebert & Pliscoff, 2006), and each riparian restoration effort should aim to restore the plant community that was historically present. However, where degradation and land use conversion limit habitat restoration to historical conditions, alternative forest composition and structure is better than no improvement, and can help maintain minimum ecosystem functions and create habitat conditions that facilitate species movement (Gann et al., 2019). In the case of land dedicated to non-native forest plantation, management of understory to increase diversity and complexity would help improve the habitat conditions within these working landscapes. In addition, forest operations should follow riparian buffer regulations and use strategies that do not damage the riparian buffer.

Habitat restoration along rivers may not fully connect habitat, as wide rivers function as a barrier for dispersal. Rivers can act as barriers especially at their outlets, where they reach their maximum width (Chesser, 1999). For example, for the Black-throated Huet-huet, the lower Biobio river, > 1 km width, acts as a barrier for north–south dispersal that explains the split from the Chestnut-throated Huet-huet (Chesser, 1999). Similarly, the Biobio river and Mapocho river limit dispersal of a widespread lizard (*Liolaemus tenuis*) (Muñoz-Mendoza et al., 2017). However, most rivers are not wide enough to be full barriers for species movement (Muñoz-Mendoza et al., 2017), and species may still maintain connected populations across large rivers in their headwater regions (Chesser, 1999).

Landscape habitat connectivity is beneficial for many species, but it may not be relevant for all. For example, restoring habitat connectivity may not be the best conservation strategy for species with small populations that are constrained to a few isolated habitat patches (Falcy & Estades, 2007). To avoid extirpation or population inbreeding other strategies may be more appropriate, such as expanding suitable habitat area in the immediate vicinity of existing habitats, reducing exploitation or predation by domestic animals, or translocation of new individuals, depending on what factors are responsible for small population size. However, habitat connectivity provided by linear corridors can help maintain overall biodiversity and population levels of many species (Gilbert-Norton et al., 2010; Resasco, 2019).

4.1. Landscape planning and restoration implementation implications

Restoration of habitat connectivity across broad extents can partially mitigate the negative effects on wildlife of land cover degradation and conversion, as well as anthropogenic climate change, by allowing wildlife to move among remaining habitat patches. Our study, in

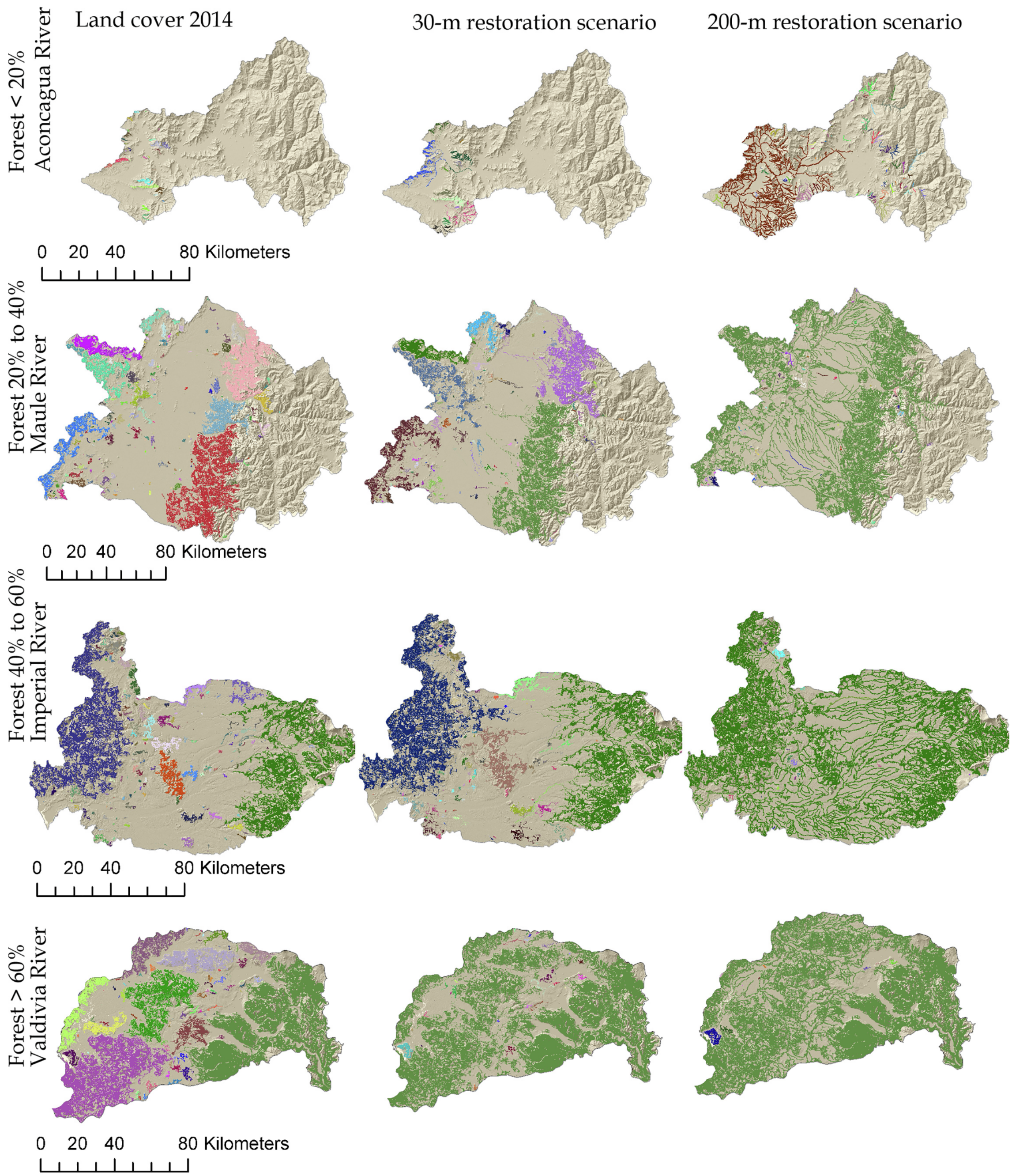

Fig. 3. Examples of forest connectivity using minimum habitat requirement of Black-throated Huet-huet under land cover in 2014 (left column), and under riparian restoration scenarios of 30-m (middle) and 200-m (right). We displayed four watersheds within our study area on a gradient of forest amount from < 20% forest (upper row) to > 60% forest (bottom row). Within each watershed, colors represent forests that form a continuous cover or that are connected by corridors. The Aconcagua and Maule watersheds, in the Mediterranean region, are out of the range of distribution for the Black-throated Huet-huet. We included here to demonstrate the effect of the restoration scenarios were forest cover is low. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

concert with other studies (Clerici & Vogt, 2013; de la Fuente et al., 2018; Fremier et al., 2015), shows that restoration of riparian buffers in accordance with existing regulations designed with other goals in mind, such as soil retention and water quality, can restore large-scale habitat connectivity for wildlife. We show that restoration conducted at a range of buffer sizes can increase connectivity for species with different habitat size requirements. In ecoregions where little habitat remains, wider buffers are necessary to increase habitat connectivity, while narrower buffers can be sufficient where habitat amount is at intermediate levels or above. Thus, depending on the ecoregional conditions, there is some flexibility with regard to the width of riparian buffer restoration that can have a positive effect on functional connectivity, while the restoration and protection efforts can accommodate socioeconomic and cultural needs of local communities.

Our study also provides a first estimate of the extent of land that could be restored in proximity to rivers. Using relatively coarse grained sources of information about location of rivers and ecological conditions for tree growth, we estimated that of ~9 M ha of land within 200-m of rivers, 2 M ha may be restored as forest. The restorable land amount is 0.3 M ha when a 30-m buffer is applied. These estimates can be useful in planning for enforcement of existing regulation. In addition, managers and planners can use this baseline information to guide

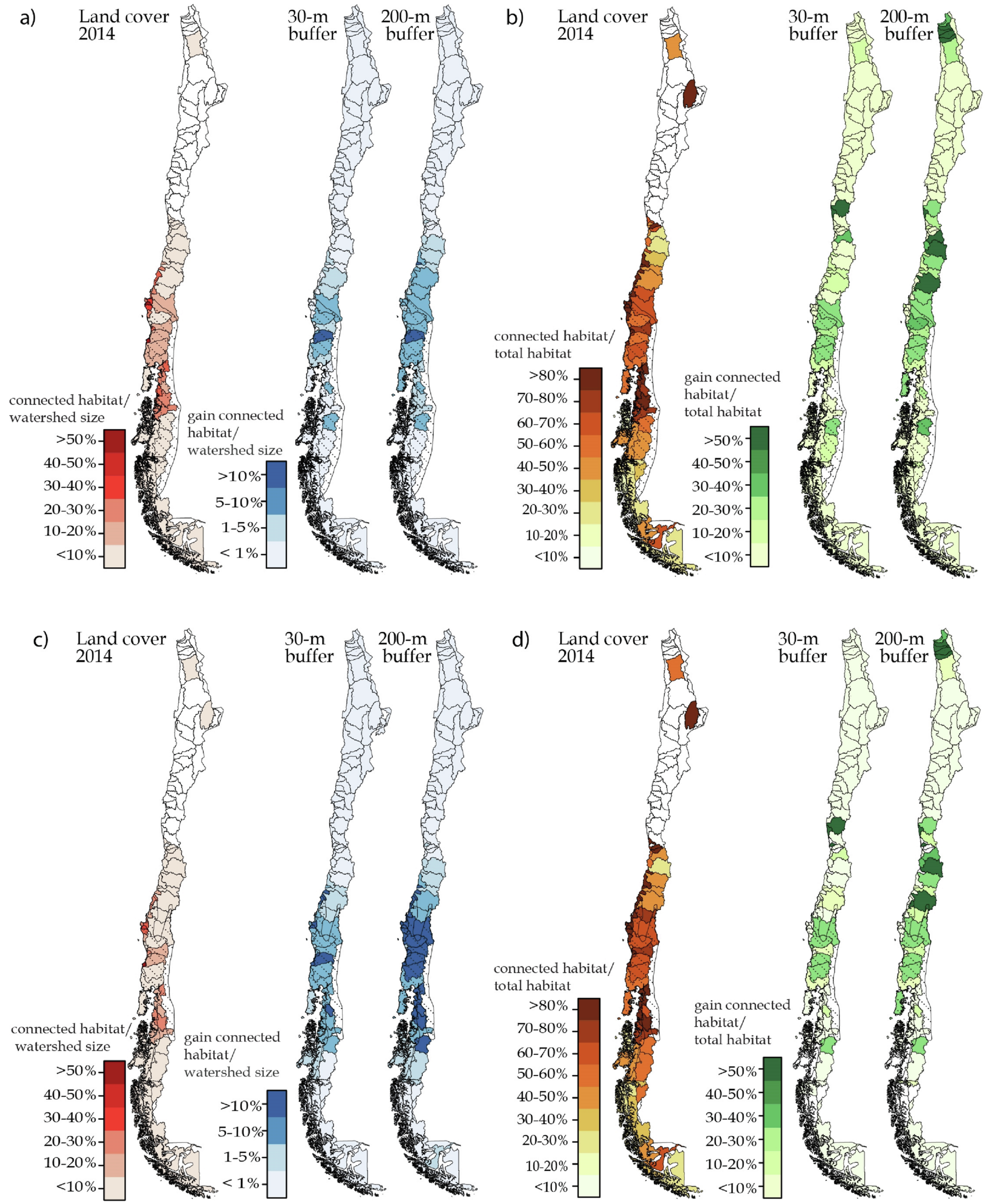

Fig. 4. Upper panel shows forest connectivity modeled using Black-throated Huet-huet minimum habitat size requirement, and lower panel shows forest connectivity modeled using Pudú minimum habitat size requirement. The dashed polygon is the range of distribution for each species. In a and c) the Equivalent Connected Area index over watershed size (red color gradient) ranged from 0% to 50%. The restoration scenarios lead to a small increase in new forest habitats for both species, as it is shown by the small gain in habitat connectivity relative to the size of the watersheds (blue color gradient). b and d) the Equivalent Connected Area index over total habitat (brown color gradient) ranged from 0% to 100%. The restoration scenarios mostly increased the connectivity between existing habitats up to 50% of the Relative Equivalent Connected Area (green color gradient). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

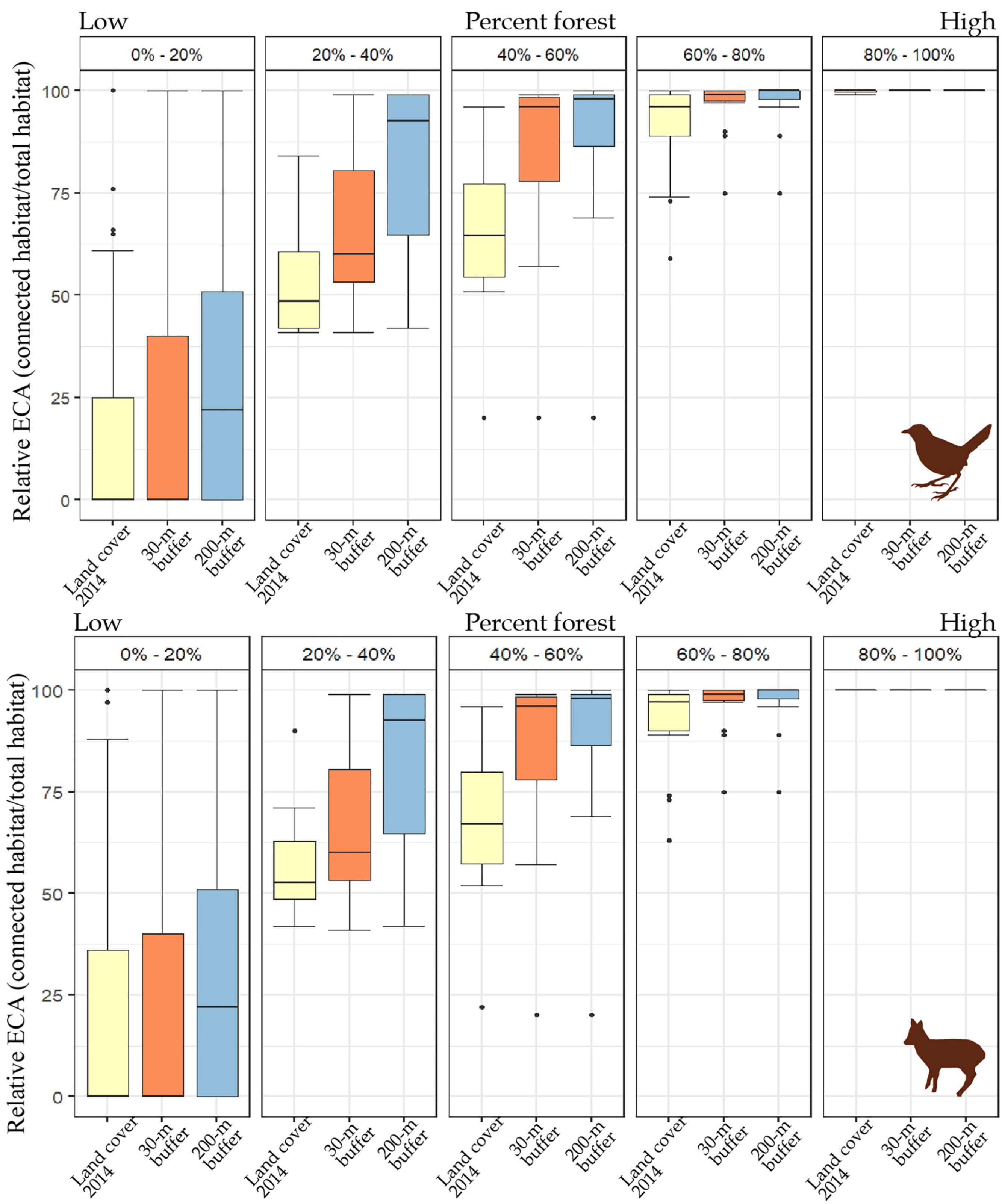

Fig. 5. Relative Equivalent Connected Area (ECA) for the land cover in 2014, 30-m and 200-m riparian restoration scenarios modeled using the Black-throated Huet-huet (upper panel) and the Pudú (lower panel) minimum habitat requirements. Boxplots show change in median and quantiles boundaries across 99 watersheds, including watershed out of the species range of distribution, that we grouped from low (left) to high percent forest (right). The five classes we used are: 0%–20% forest (n = 61), 20%–40% forest (n = 8), 40%–60% forest (n = 12), 60%–80% forest (n = 15) and > 80% (n = 3).

ongoing broad-scale restoration efforts, in conjunction with socio-economic information, for prioritization and implementation at the parcel level (e.g., Tomer, Dosskey, Burkart, James, Helmers & Eisenhauer, 2009; Chazdon et al., 2017). Ultimately, forest planting, aimed primarily at increasing ecosystem services (e.g., increasing carbon stock and water quality; Dosskey, Qiu, & Kang, 2013; Qiu & Dosskey, 2012), can be strategically located to also reduce the negative effects of habitat loss and fragmentation.

5. Conclusion

We assessed the effect of restoring riparian forests on habitat connectivity in accordance with existing regulations and identified which kinds of landscapes and what buffer sizes would most increase habitat connectivity for forest fauna. Our study provides baseline information about the effect of riparian restoration on forest landscape structural connectivity. We quantified the extent of land available for restoration along rivers and show that riparian restoration could be an efficient way to connect landscapes, because relatively small increases in overall forest area increased connectivity substantially. These findings are relevant for conservation planning in Chile, and in other countries, where information about species habitat size requirements is scarce.

CRediT authorship contribution statement

Isabel M. Rojas: Conceptualization, Methodology, Writing - original draft, Formal analysis, Visualization, Funding acquisition. **Anna M. Pidgeon:** Conceptualization, Methodology, Writing - review & editing. **Volker C. Radeloff:** Conceptualization, Methodology, Writing - review & editing.

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