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Environmental and ecological architects: Guidelines for the Chilean temperate rainforest management derived from the monito del monte (*Dromiciops gliroides*) conservation

Arquitectos ambientales y ecológicos: Pautas para la gestión ambiental del bosque templado lluvioso de Chile derivadas de la conservación del monito del monte (*Dromiciops gliroides*)

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ABSTRACT

Land use change is one of the main biodiversity threats. Due to this change, natural habitats such as the South American temperate rainforests have been rapidly degraded, fragmented, and lost. Consequently, the management and conservation of the remaining forest is a priority and having an appropriate environmental policy is mandatory for this purpose. Conservation actions in the temperate rainforest have been addressed from an individual species perspective, giving less attention to the ecosystem level conservation. Moreover, conservation-related information has not reflected yet on environmental policy development. We used the case study of the monito del monte (*Dromiciops gliroides*) to illustrate how our current ecological and conservation knowledge of a species could be used to generate a new environmental policy. *Dromiciops gliroides* is a forest-dependent species with an important ecological role and quite unique evolutionary status. In order to guarantee the persistence of *D. gliroides*, we propose two habitat management components to be incorporated in management plans: structure and connectivity. Structure refers to spatial arrangement and key structural elements that determine habitat quality and connectivity refers to functional connectivity at the landscape level. The conservation of the monito del monte might also contribute to the conservation of many other forest-dependent species. By conserving such species it will be possible to conserve the ecological interactions and the eco-evolutionary processes, which ultimately determine the conservation of the temperate rainforest.

Key words: environmental policy, management plan, natural regeneration, plant-animal mutualism, rainforest.

RESUMEN

El cambio de uso de la tierra es una de las principales amenazas a la biodiversidad. Hábitats naturales como el bosque templado lluvioso de Sudamérica han sido degradados, fragmentados y eliminados rápidamente. En consecuencia, es prioritario el manejo y conservación de los remanentes, para lo que es necesario contar con una política ambiental acorde. Las acciones de conservación referentes al bosque lluvioso templado se han abordado mayormente desde una perspectiva de especies individuales, con poco énfasis en la conservación a nivel de ecosistema. Más aún, la información generada en este ámbito tampoco ha permeado en el desarrollo de políticas ambientales. Utilizamos el estudio de caso del monito del monte (*Dromiciops gliroides*) para ilustrar cómo el conocimiento actual en ecología y conservación de una especie puede ser utilizado para generar una nueva política ambiental. *Dromiciops gliroides* es una especie dependiente del bosque, con un importante rol ecológico y un gran interés evolutivo y de conservación. Para garantizar su persistencia, proponemos dos componentes de gestión del hábitat, a incorporarse en los planes de manejo: la estructura y la conectividad. La estructura hace referencia al arreglo espacial y la presencia de elementos estructurales clave que influyen en la calidad del hábitat, mientras que conectividad se refiere a la conectividad funcional del paisaje. Conservando al monito del monte, se conservarían también otras especies dependientes del bosque y así las interacciones ecológicas y los procesos ecoevolutivos, que determinan finalmente la conservación del bosque lluvioso templado.

Palabras clave: bosque lluvioso, mutualismo planta-animal, plan de manejo, política ambiental, regeneración natural.

INTRODUCTION

Human activities have modified natural habitats since prehistoric times, with a remarkable intensification after the arrival of the industrial era (Armesto et al. 2010). As a result, there is currently a biodiversity loss crisis. Even though this situation has been acknowledged in the last decades, the environmental policies and conservation actions have only been developed quite recently (Butchart et al. 2010). Land use change is one of the most worrisome threats to biodiversity worldwide (Sala et al. 2000) and it is closely related to habitat loss, fragmentation, and transformation (Chapin III et al. 2000). All these factors might compromise the long-term persistence of many species, given that their life history traits determine their sensitivity to habitat modifications (Vásquez & Simonetti 1999, Vergara & Armesto 2009).

Special attention has been given to hot-spot sites around the world (Myers et al. 2000, Mittermeier et al. 2005) in order to preserve ecosystems with high biodiversity and endemism levels, currently threatened by human actions. Among them, high endemism in temperate ecosystems, such as the South American temperate rainforest (SATR) has been less studied than tropical ecosystems. This particular forest is facing rapid fragmentation and loss (Echeverria et al. 2006, 2007), because of the expansion of urban centers and farming activities (Armesto et al. 2010). The remaining SATR stands are highly fragmented, immersed in a complex mosaic of anthropogenic matrices. Such matrices range from plain grasslands to commercial forest plantations, increasing edge effects (Bentley 2008) and reducing habitat quality.

Conservation issues at the SATR have been mostly handled species-by-species, focused on species with critical conservation status. However, the conservation of functionality of these forests has not been taken into consideration. Few studies have addressed the impact of human disturbances on ecological interactions (e.g., Valdivia et al. 2006, Simonetti et al. 2007, Valdivia & Simonetti 2007, Martinez-Harms & Gajardo 2008). Moreover, habitat degradation, loss, and fragmentation could disrupt key mutualisms (e.g., Rodríguez-Cabal et al. 2007) and negatively affect natural regeneration. As the SATR has a highly endemic biota, plant-animal mutualisms (such as pollination and seed dispersal) are remarkably important in maintaining biodiversity (Aizen et al. 2002). Therefore, an ecosystem conservation approach would be preferred, rather than single species-based conservation actions.

For a successful habitat conservation approach, appropriate environmental policies are necessary, aiming to create a national framework for management and conservation. However, environmental policy and biodiversity conservation studies are commonly treated separately (e.g., Margalida et al. 2010), each focusing on resolving their particular problems without an explicit connection. Environmental management and conservation sciences share many ecological elements, even if they usually operate at different spatial scales. In this short essay, we aim to use the case study of an endemic South American ancient marsupial, to show an example of an explicit connection between research conducted on the ecology and conservation of a particular species. We propose the development of environmental policies intended to successfully manage the SATR, considering its functional and structural aspects.

DROMICIOPS GLIROIDES AS A MODEL SPECIES

The monito del monte (*Dromiciops gliroides* Thomas) is considered a conservation priority for being the only extant species of the Microbiotheria Order (Marshall 1978), and because of its ecological role as seed disperser of many native species (Amico et al. 2009). Thus, *D. gliroides* can help significantly to the natural regeneration of the native vegetation (García et al. 2009, Carmona et al. 2010). This species has not been studied in detail until the last decade. Recent research has shown that *D. gliroides* is not as scarce as it was assumed to be, when specific sampling methods were developed (Fontúrbel & Jimenez 2009, Fontúrbel 2010). We also have a much better understanding of this species' tolerance to habitat degradation, emphasizing its role as a regeneration agent. In spite of such tolerance, studies regarding spatial ecology have shown that *D. gliroides* can disperse through riparian corridors (Smith-

Ramírez et al. 2010), but cannot move across open habitats, such as prairies (Fontúrbel et al. 2010). Such behavior precludes its dispersal among forest remnants immersed into non-forested matrices, experimenting a "fence effect" (Lindenmayer et al. 1999).

Dromiciops gliroides is an endemic marsupial of the Chilean and Argentinean SATR distributed from Los Queules National Reserve (35° S) to Chiloé island (44° S), comprising both Coastal and Andes ranges and the intervening lowlands (Kelt & Martínez 1989, Lobos et al. 2006). This species is morphologically and physiologically adapted to cold and moist forests (Hershkovitz 1999, Bozinovic et al. 2004). It was thought to be restricted to old-growth native stands dominated by *Nothofagus* spp. and *Araucaria araucana* (Hershkovitz 1999). However, recent research has shown that *D. gliroides* is also found in small (< 5 ha) Myrtaceae-dominated second-growth forest fragments (Fontúrbel et al. 2010), in which it has shown similar population densities than those found in old-growth fragments (see also Celis-Diez 2010, Smith-Ramírez et al. 2010), as long as these fragments retain key structural elements such as fallen logs, stumps, leaf litter, snags, shrubs, and a dense bamboo cover. In Argentina, nevertheless, forest fragmentation has shown a negative effect on *D. gliroides*' densities (Rodríguez-Cabal et al. 2007).

Small-bodied species like this marsupial are usually associated to structurally complex habitats. In that sense, structural complexity determines habitat texture, which also influences mobility and shelter-provisioning (Bro-Jørgensen 2008, Fischer et al. 2008). However, human disturbance can significantly alter habitat complexity for *D. gliroides*. Anthropic pressures can change canopy height and cover, branch diameter and density, leaf litter abundance, vine abundance, moss abundance, shrub cover, bamboo cover, as well as the presence of fallen logs, stumps, and snags (Jaña-Prado et al. 2006). Such changes can dramatically reduce cavity availability (i.e., nesting sites) by removing coarse woody debris (usually used as firewood), as has been shown for forest cavity nesting birds (Cornelius et al. 2008, Cockle et al. 2010) and marsupials (Lindenmayer et al. 1999, Gibbons et al. 2002). Despite this, there is no formal study on cavity limitation for *D. gliroides*. The use of nest boxes and its increasing occupancy trend over time (Franco 2009) suggest that natural cavities might in fact be a limiting resource for this species in second-growth stands. Nesting boxes occupancy increased from 20 % to 40 % in three years (LM Franco, personal communication, 2010).

The reduction of branch, shrub, and bamboo density might diminish shelter sites and intra-fragment dispersal paths. Such habitat structure seems essential in order to attain long-term persistence (Vergara & Schlatter 2008). Those aspects are well documented for forest-dependent birds. Forest bird richness, abundance, and guild composition has shown significant changes as a function of habitat structure (Diaz et al. 2005). Specifically, structural simplification would cause a decline on forest bird diversity. Moreover, structural components such as understory density might determine movement possibilities for dispersal-limited species, such as rhynocriptids (e.g., *Scelorchilus rubecula*, *Pteroptochos tarnii*) (Castellón & Sieving 2006a, 2007).

In summary, habitat degradation could negatively affect *D. gliroides* in two main aspects: shelter and food provisioning. Shelter would be a limiting resource when cavities on live trees and fallen logs are reduced by human action. Also nesting materials (mosses and bamboo leaves; Jiménez & Rageot 1979) could be a limiting resource on degraded forests (Diaz et al. 2006). On the other hand, the reduction of vines and understory vegetation would reduce food (i.e., fleshy fruits and insects) availability, as well as potential dispersal paths needed to search for food (Jaña-Prado et al. 2006, LM Franco, personal communication, 2010) and compromise mobility (Gallardo-Santis et al. 2005). Consequently, habitat structure could limit habitat use possibilities (Vergara & Schlatter 2008, Vergara & Armesto 2009), as reported for other forest-dependent species (e.g., Sieving et al. 2000, Reid et al. 2004).

STRUCTURE AND CONNECTIVITY: LINKING CONSERVATION RESULTS WITH ENVIRONMENTAL POLICY

A sound environmental policy should be based on hard ecological knowledge (Lindenmayer

1999). Ecological and conservation knowledge should be used to design forest conservation and management plans at the scale of the biome. Maintaining ecosystem functionality and its evolutionary trajectory depends on preserving the ecological interactions. Previous works highlighted understory birds as umbrella species for SATR conservation (e.g., Castellón & Sieving 2007). Here, we go further by proposing the use of an endemic mammal, with an exceptional ecological role. Our current ecological knowledge on *D. gliroides* points to its outstanding role maintaining pollination and dispersal services (Aizen 2003), on which the ecosystem persistence and identity relies, and supports it as a model species for conservation and management (Lindenmayer et al. 2002). Being the sole disperser of the native mistletoe *Tristerix corymbosus* (Amico & Aizen 2000, Amico et al. 2011), this marsupial guarantees the food supply for many other species, especially for the hummingbird *Sephanoides sephaniodes*, which depends on this mistletoe for feeding in winter (Aizen 2003). Conserving mutualists has an exceptional ecosystem conservation value, considering that about 75 % of the SATR plants depend on such mutualisms (Aizen & Ezcurra 1998).

In order to maintain *D. gliroides'* ecological dynamics that may serve as a model species to maintain SATR ecological processes, we propose two key components that should be considered on the environmental policy: habitat structure and connectivity.

Habitat structure

Habitat structure component has two main axes: geometry and fine-grain structure. The former operates at the landscape scale and is determined by the spatial arrangement of patches, while the latter does it at the patch scale. Thus, landscape attributes such as fragment size, shape, and its spatial distribution (randomly, uniformly, or aggregated in patches) determine dispersal possibilities as well as the amount of suitable habitat available for a particular species (Fahrig 1997, 2003, Lindenmayer & Fischer 2006). Additionally, those landscape attributes also determine the extent of edge effects (Ries & Sisk 2004). Small and irregular fragments will experiment larger edge effects than large and rounded patches. Regular fragments have larger core areas than irregular ones and hence, larger potential carrying capacities for the species therein (Castellón & Sieving 2007).

Additionally, metapopulation dynamics could be achieved if patches are large and close enough to maintain local populations, and would allow inter-patch dispersal (Wiens 1997). Despite the fact that *D. gliroides* metapopulation dynamics has not been assessed yet, telemetry (Franco 2009, Fontúrbel et al. 2010) and corridor-use evidence (Smith-Ramírez et al. 2010) suggest that it would be similar to Castellón & Sieving's (2007) model for *S. rubecula*. In that sense, spatially-explicit scenarios should be used in order to estimate the proportion of SATR remnants that would constitute suitable habitat for forest-dependent species. If this consideration is taken into account when managing forest remnants, the amount of suitable habitat for *D. gliroides* and other forest species could be maximized.

On the other hand, fine-grain structure axis refers to the presence and quantity of key structural elements in each forest patch. Structural elements such as canopy height and cover, cavities, branches, vines, mosses, and others determine that microhabitat conditions could be seen as niche axes (Vásquez 2005). The presence and abundance of those structural elements determine the habitat quality of each forest remnant (Beyer et al. 2008, Vergara & Armesto 2009) and could be lost due to human action: directly, through its removal for firewood or other uses, and indirectly, by livestock grazing. Recent work (Rodríguez-Cabal 2008, García et al. 2009) has shown that, in Argentina, the presence of *D. gliroides* is related to *T. corymbosus* abundance at a smaller scale. However, this pattern was not detected in Chile (Smith-Ramírez et al. 2010). At a broader scale, *D. gliroides* presence is associated with bamboo cover (see also Patterson et al. 1990). Bamboo cover is also a major factor for understory birds (e.g., *Sylviorthorhynchus desmursii*), influencing abundance of invertebrates as food resource (Reid et al. 2004). An abundant understory may also have a positive effect on *D. gliroides*, by providing invertebrates that constitute an important item of its diet (Jiménez & Rageot 1979, Quijano 2008).

Connectivity

Two axes determine the connectivity component: landscape composition and the nature of the surrounding matrix. Forest composition relies on how forest patches of different size classes are distributed along a heterogeneous landscape. This aspect, closely related with the first structural axis, is fundamental to determine functional connectivity (e.g., Castellón & Sieving 2007). Castellón & Sieving (2006b) determined that > 25 % of non-open habitat surrounding forest patches could have a significant effect on *S. rubecula* occupancy even in small (< 10 ha) fragments. A similar situation could be expected for *D. gliroides*, which is known to be able to disperse through dense scrublands (Fontúrbel et al. 2010). Considering the limited dispersal abilities of *D. gliroides* (short distances of 100 to 200 m), its movement through the landscape requires closer patches and forested corridors, with some vertical structural complexity (Fontúrbel et al. 2010, Smith-Ramírez et al. 2010). Empirical evidence has shown that corridors > 25 m wide can allow *D. gliroides* movement and thus persistence (Smith-Ramírez et al. 2010), which is very similar to the value estimated by Sieving et al. (2000) for *S. rubecula*.

Because of the positive relationship between landscape connectivity and ecological connectivity (Lindenmayer & Fischer 2006), a diminished *D. gliroides* landscape dispersal would result in less ecological connectivity. Losing ecological connectivity would represent less inter-fragment dispersal for many native plants, and hence less gene flow. The permeability of the surrounding matrix (Ricketts 2001), ultimately determines whether this species would be capable to disperse throughout, as well as the species abundance and composition in each fragment (Ewers & Didham 2006). A non-forested matrix will preclude *D. gliroides* dispersal, even though forest remnants are close to each other (Fontúrbel et al. 2010), confining local populations to isolated patches with no chances of gene flow or rescue effects. The amount and quality of vegetation cover would ultimately determine the willingness of forest species to enter potential corridors (Sieving et al. 2000).

Molecular evidence has shown minimum *D. gliroides* genetic differentiation levels, because of the unrestricted gene flow along its distributional range (Himes et al. 2008). Therefore, the movement restrictions that human disturbance impose could severely affect the evolutionary trajectory of this marsupial. Increasing genetic differentiation among forest remnants and causing allelic diversity loss could also change its eco-evolutionary dynamics (Kinnison & Hairston 2007), modifying the local ecological interactions, and its role as a selection agent.

Joining structure and connectivity with environmental policy

The current Chilean legislation (Native Forest Law 20283, approved in 2008) considers the formulation of native forests management plans. However, the spatial configuration of the SATR is not taken into consideration under this legal framework, overlooking core habitats, key structural elements (Vergara & Schlatter 2008), and functional connectivity. Moreover, cutting methods prescribed in the Chilean law (i.e., heavy shelter-wood and strip cutting) for forest regeneration does not consider forest-dependent species, which would decrease as a result of structural changes (Vergara & Schlatter 2008). Consequently, the whole ecological and evolutionary dynamics of the SATR has been overlooked. On the contrary, if structure and connectivity were taken into account for the elaboration of environmental policies, a more realistic ecosystem conservation program would be achieved (Fig. 1).

Considering the current habitat loss trend (Echeverria et al. 2006), it is imperative to manage the remaining rainforest fragments appropriately, contemplating integral management plans. The absence of management of timber stocks will cause its collapse within one or two decades (Armesto et al. 2010). Consequently, forest recovery should be included in the legal framework. Future land policy should also incorporate social values and ecological factors instead of being based mostly on economic reasoning

(Armesto et al. 2010). Our proposal may help to incorporate the ecological factors into this new policy, but socio-economic drivers of land use change should also being considered.

In the same sense as the monito del monte was proposed here as a model species, birds also were used as conservation umbrellas. In that case, Willson & Armesto (2003) proposed five key management recommendations: (1) maintaining the extant forest patches, (2) using wooded windshields, (3) harvesting planning, (4) education, and (5) research. Although such general recommendations are extremely valuable for incorporating the ecological dimension into environmental policy, they ignore the spatial component. A spatially-explicit approach as the one we propose here might complement these recommendations and hence help developing better and more functional and sustainable policies.

Integrating these structural and connectivity components derived from studying the monito del monte would allow improving the current environmental policy in four main aspects:

(1) Promoting preservation of the extant remnants and restoring previously degraded or deforested areas, in order to increase landscape connectivity. Connecting several forest patches of different size classes would have a larger positive effect than preserving a few large and isolated remnants (Prugh et al. 2008). This scenario would allow inter-patch connectivity, benefiting *D. gliroides* and many other forest-dependent species that cannot disperse through a non-forested matrix (Castellón & Sieving 2006b). This outcome would help maintain the ecosystem functionality, incorporating trophic complexity (Duffy et al. 2007). Additionally, preserving such animal species also would

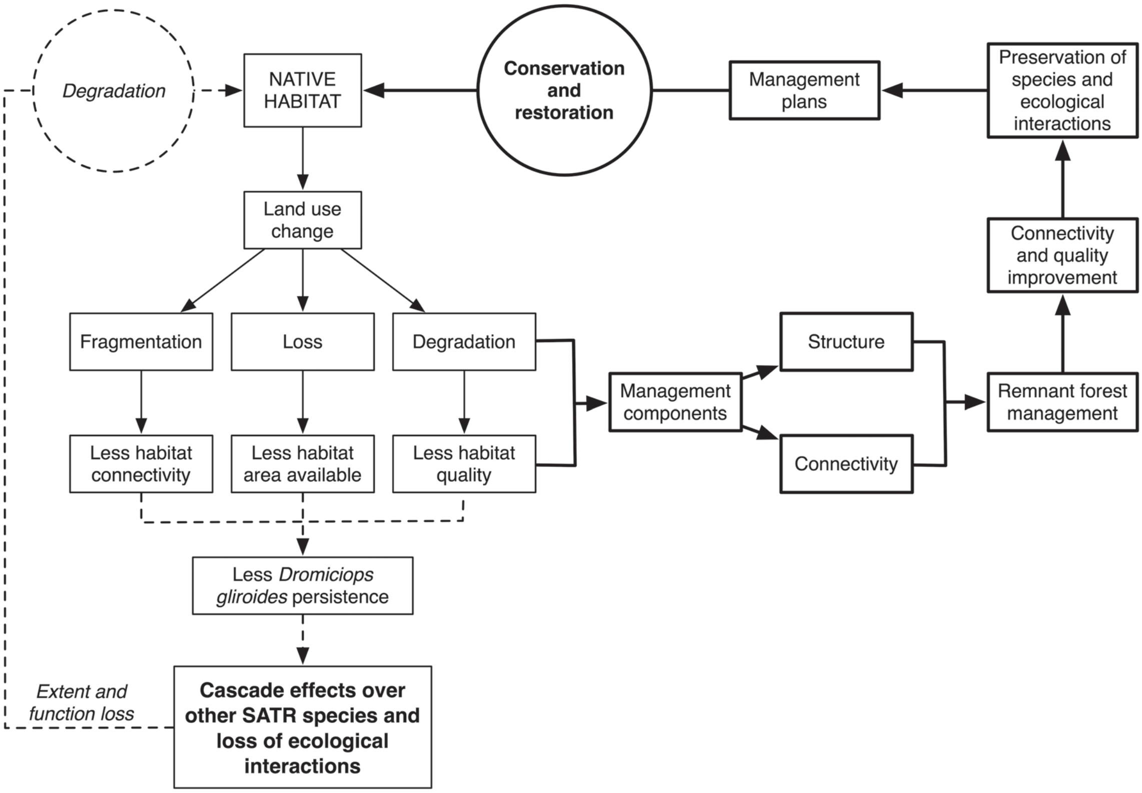

Fig. 1: Summary chart. Regular lines represent the current situation. Dashed lines represent what would happen if no actions were taken. Bold lines represent what would happen if the proposal were implemented. Circles present the final result for the native forest.

Esquema resumen. Las líneas normales muestran la situación actual. Las líneas punteadas ilustran lo que pasaría si no se toman acciones. Las líneas gruesas muestran lo que pasaría si se implementa la propuesta. Los círculos representan el resultado final para el bosque nativo.

have a positive effect on plant species conservation, particularly specialist species that rely on mutualistic interactions (Aguilar et al. 2006).

(2) Regulating human activities over the extant forest remnants, in order to maintain the habitat quality (Jaña-Prado et al. 2006), on which also many understory bird species depend (Reid et al. 2004, Diaz et al. 2005). Those regulations should avoid the loss of key structural elements to firewood extraction or livestock grazing, aiming to maintain habitat quality and to promote natural regeneration of disturbed areas.

(3) Maintaining the ecosystem value, through services and goods (Martinez-Harms & Gajardo 2008). This could be achieved by conserving the habitat, the species, and the ecological interactions. Regulation and habitat processes are essential for the maintenance of all natural processes (Martinez-Harms & Gajardo 2008). Particularly, conserving *D. gliroides* would allow maintaining the natural regeneration services.

(4) Generating a new environmental policy for the SATR, considering the heuristic value of the current ecological knowledge as the cornerstone of management plans.

In summary, conservation knowledge and environmental policies are closely related to each other, which is why they should not be treated separately. The case study of *D. gliroides* has illustrated this important interaction between scientific and policy-making processes. Following these simple recommendations would help conserve many other native species, which also rely on habitat quality, structure, and connectivity for its long-term persistence, as well as maintaining their eco-evolutionary dynamics (Kinnison & Hairston 2007). With an open mind, our "environmental architects" might find the essential benefits of learning from the "ecological architects", such as the monito del monte, for the management and conservation outcomes to show significant improvement.

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