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Systematic planning of disconnection to enhance conservation success in a modified world

Virgilio Hermoso[a,c,*], Stephanie R. Januchowski-Hartley[b], Simon Linke[a]

[a] Centre Tecnologic Forestal de Catalunya, Crta. Sant Llorenc de Monunys, Km 2, 25280 Solsona, Lleida, Spain
[b] Department of Life Sciences, Texas A&M University-Corpus Christi 6300 Ocean Dr., Corpus Christi, TX 78412, United States
[c] Australian Rivers Institute and Tropical Rivers and Coastal Knowledge, National Environmental Research Program Northern Australia Hub, Griffith University, Nathan, Queensland, 4111, Australia

HIGHLIGHTS

- Biodiversity conservation in modified areas can benefit from prescribed disconnections.
- Barriers can be a cost-effective way of addressing threats.
- Barriers should be systematically planned considering ecological and socio-economic cost–benefits.
- This will ensure socially acceptable and ecologically effective use of disconnections.

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ABSTRACT

Maintaining spatial–temporal connectivity for conservation is necessary to allow the persistence of ecological processes and the biodiversity they sustain. However, conservation practice in human-modified environments can also benefit from prescribed disconnection through the implementation of barriers. Barriers, such as fences or dams, and buffer zones can be a cost-effective way of addressing threats caused by a globally connected world, such as the propagation of invasive species and diseases, creating refuge areas for native biodiversity and helping reduce economic losses caused by native wildlife or invasive species. Despite the global attention that disconnection has received, no clear framework exists to guide the allocation of barriers for conservation management. Here we propose that the implementation of barriers for conservation should be systematically planned, considering ecological trade-offs for multiple species (easing threats vs. interruption of ecosystem processes) and socio-economic cost–benefits (implementation cost vs. reduced human–wildlife conflicts), rather than using ad-hoc opportunistic criteria or accommodating conservation needs for individual species. Such a systematic approach is necessary to ensure both socially acceptable and ecologically effective use of disconnections as a conservation tool and ideally planned across different realms so co-benefits or trade-offs can be accounted for. However, any implementation of disconnection for conservation should be cautiously considered if uncertainty in effectiveness of the barrier and ecological impacts to other species are high. We also suggest the need for improved approaches to monitoring to learn from previous successes and failures. Our recommendations should guide the systematic evaluation and allocation of barriers to help enhance the value of this conservation tool in the face of increasing propagation of threats worldwide. However, new tools and collaborative frameworks across different realms are needed to help stakeholders make better informed decision.

1. Introduction

Spatial–temporal connectivity (from here connectivity), or the degree to which the landscape facilitates or impedes movement, plays a key role in maintaining ecological processes that are essential for the persistence of populations and species (Driscoll et al., 2013). These ecological processes linked to connectivity include dispersal and migrations, gene flow and transport of energy and matter among others. However, natural patterns of connectivity have been transformed by the introduction of artificial structures, such as fences, roads, railways and dams, and through habitat modification and destruction caused by human land use (Becker et al., 2007).

The importance of connectivity for environmental conservation has attracted much attention from conservation scientists for decades.

* Corresponding author at: Centre Tecnologic Forestal de Catalunya, Crta. Sant Llorenc de Monunys, Km 2, 25280, Solsona, Lleida, Spain.
E-mail address: virglio.hermoso@gmail.com (V. Hermoso).

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Simberloff and Cox (1987) questioned the cost-effectiveness of corridors for conservation, arguing that the investment required to create and maintain these corridors could be better directed to land acquisition or other conservation actions (see also Hodgson et al., 2009 for a more recent review). There have also been supporters of maintaining existing and restoring lost connectivity. Noss (1987) argued for the precautionary principle, suggesting that it is prudent to maintain connectivity, even when there is no direct evidence of its benefit. The importance of connectivity issues in conservation science and management has continued to grow in the last two decades, evidenced by the exponential increase of publications and citations of publications related to landscape connectivity (see Crooks and Sanjayan, 2006; Moilanen et al., 2009; Linke et al., 2011 for some examples). In turn, novel methods have been developed to integrate spatial and temporal connectivity in the design of marine, terrestrial and freshwater reserves (Klein et al., 2009; Beger et al., 2010; Hermoso et al., 2011). There have also been numerous efforts to both identify and remediate structures that constrain natural ecosystem connectivity. For example, the remediation of road culverts can be an effective solution to enhance longitudinal connectivity for fish movement (Poplar-Jeffers et al., 2009; Pepino et al., 2012) and the construction of under- and over-pass structures can significantly reduce the effect of roads on mammals, reptiles and amphibians (e.g., Lesbarrères and Fahrig, 2012; Polak et al., 2014).

Despite its unquestionable value in the conservation toolbox, maintaining or restoring connectivity should not be generalized as a conservation solution, especially when planning and implementing conservation actions in highly modified environments (Simberloff and Cox, 1987). This is because there are unavoidable trade-offs between the benefits of connectivity for native biodiversity and the ecological risks associated with reconnecting disturbed and undisturbed areas, such as reconnecting an area where an invasive species is present with an area where it does not yet occur (McLaughlin et al., 2012). Other threats such as pollution or human–wildlife conflicts can also expand as human-made barriers are removed.

Indeed, prescribed disconnection (intentional isolation of populations or systems) through the use of hard (e.g., dams, fences) or soft (e.g. buffer areas around core protected areas) barriers can be a cost-effective way of minimizing or completely halting the propagation of threats (Table 1 and references therein). Both hard and soft barriers can be used to facilitate management of endangered species or ecosystems processes (e.g., sediment and nutrient retention; Powers et al., 2013) by creating enclosed areas or spatial buffers that can act as, or support, refuge or population sources (e.g., Frank et al., 2014). There have been several recent reviews (e.g., Hayward and Kerley, 2009; Rahel, 2013) about conservation opportunities of artificial disconnection in terrestrial, freshwater and marine ecosystems, respectively (see also Table 1 for more examples). However, the effectiveness and/or impacts of disconnections on the maintenance of processes and biodiversity persistence remain unclear (Hoare et al., 2010), and little has been said about how to best manage the ecological and socio-economic trade-offs related to the use of disconnection as a conservation tool (but see Bode and Wintle, 2009; Packer et al., 2013).

In this paper, we evaluate management options for using barriers as a conservation tool and highlight the need for new approaches to enhance decision-making when prescribing the use of disconnection for conservation. In this way, we shed light on the need for new approaches to managing disturbances for multiple species (Richardson, 2012) in a rapidly changing world. To ensure both socially acceptable and ecologically effective use of barriers for conservation, we propose a systematic approach for evaluating and trading off complex ecological and socio-economic factors that are likely to require consideration when prescribing disconnections. We suggest that systematic planning methods should guide future decisions

Table 1
Examples of different barriers used in terrestrial, freshwater and marine environments, conservation benefits and impacts. H and S stand for hard (e.g., dams, fences) and soft (buffers around core protected areas) types of barrier.

Realm	Disconnection action	Conservation benefit	Socio-economic/ecological impact
Terrestrial	Fences (H)	• Invasive species (Frank et al., 2014)	• Change predator–prey relationship (Davies-Mostert et al., 2013)
		• Diseases (Bode and Wintle, 2009; Lavelle et al., 2011; Dion and Lambin, 2012)	• Increase grazing pressure within enclosed areas (Cassidy et al., 2013; Graz et al., 2012)
		• Predation pressure (overgrazing on native vegetation within enclosure area) (Boone and Hobbs, 2004; Hayward and Kerley, 2009)	• Disrupt population level interactions and movement (Hayward and Kerley, 2009; Vanak et al., 2010).
		• Reduce road kills (Clevenger et al., 2001; Jaeger and Fahrig, 2004)	• Injuries to wildlife (Rey et al., 2012)
		• Reduce animal–human conflicts (Anthony, 2007; Packer et al., 2013)	
	Buffer zones around protected areas (S)	• Reduce human–animal conflict (Fox and Madsen, 1997)	
Freshwater	Dam & electric barriers (H)	• Invasive species (McLaughlin et al., 2012)	• Constrain movement (e.g., migrations), flow and nutrient cycling (Rahel, 2013)
		• Pollution (McLaughlin et al., 2012; Powers et al., 2013)	
		• Diseases (Rahel, 2013)	
		• Avoid population sinks (Jackson and Pringle, 2010)	
		• Hybridization (Rahel, 2013)	
	Fences (H)	• Stream bank erosion (Agouridis et al., 2005)	• Corridor for invasive species; fragmentation of ecotone between terrestrial and freshwater (Loo et al., 2005)
		• Overgrazing (Jansen and Robertson, 2001)	• Constrain use of aquatic resources for economic productivity (Fensham and Fairfax, 2008)
		• Non-point source pollution (Bewsell et al., 2007)	
		• Trampling (Fensham and Fairfax, 2008)	
	Levees (H)	• Isolate floodplain refugia from threats in main channel (Jackson and Pringle, 2010)	• Reduced lateral connectivity between stream channels and floodplains (Jackson and Pringle, 2010)
Marine	Controlling ballast waters (H)	• Invasive species (Bax et al., 2007)	• Impacts on trade/commerce (Bax et al., 2007)
		• Diseases (Bax et al., 2007)	
	Buffer zones around protected areas (S)	• Reduce spill over of fishing pressure effects into marine reserve (Januchowski-Hartley et al., 2012)	
		• Reduce human–animal conflict (Januchowski-Hartley et al., 2012)	• Impacts on recreational fishing and tourism (McClanahan and Mangi, 2000)

about the retention and allocation of barriers to maximize ecological benefit and minimize potential risks and negative impacts across terrestrial, freshwater and marine realms. New tools will also be needed to help stakeholders prioritize the spatial allocation of barriers across multiple realms.

2. Management options of connectivity for conservation

Across terrestrial, freshwater and marine realms, conservation planners and practitioners are faced with making conservation decisions in landscapes that are widely modified, where natural patterns and processes have been connected or isolated by humans. For example, *naturally isolated systems*, such as oceans or river catchments, have become increasingly connected by global trade and construction of artificial canals to enable inter-catchment water transfer and transport (Katsanevakis et al., 2013). These connections open-up historical biogeographical barriers, fostering introductions and spread of non-native species and diseases into new areas (Olden, 2006). In terms of biodiversity conservation, the best management option for these systems would be to reinstate natural isolation and then restore the biogeographical barrier. However, due to economic, socio-political and technical constraints it is often infeasible to re-establish biogeographic barriers. Instead, the implementation of new legislation and policy (e.g., better control of illegal trade of species or release of ballast water) and the improvement of public awareness through education programs (so called "metaphorical barriers" sensu Hayward and Kerley, 2009) could be effective solutions for reducing the effects of these artificial connections. For example, connecting Lake Michigan to the Mississippi River via the Chicago Sanitary and Ship Canal in 1910 facilitated the migration of non-native fishes into the Great Lakes (McLaughlin et al., 2012). This connection has been mitigated by electric barriers (Rahel, 2013). However, the cost- effectiveness of these electrical barriers has been questioned, as they are expensive to maintain and are not totally effective (e.g., subjected to power outages and are ineffective for some species; Rahel, 2013).

On the other hand, *naturally connected systems* have been disconnected by an exponential increase in the incidence of artificial structures associated with human development (e.g., roads, dams) and high rates of habitat loss (e.g., deforestation or desiccation of wetlands) (Ribeiro et al., 2009). These reduced connections constrain important natural processes such as species migrations and gene exchange and the availability of energy and material that are critical for sustaining native populations and species (e.g., Becker et al., 2007). Consequently, protecting global biodiversity in this rapidly changing world will depend on our capacity to adequately manage both new and lost ecological connections to ensure persistence of native species populations and ecosystem processes, and it is likely that there is no single best solution because of unavoidable case-specific ecological and socio-economic trade-offs (see below) that need to be evaluated. Increasing connectivity is desirable for recovering both species populations and ecological processes (Poplar-Jeffers et al., 2009; Lesbarrères and Fahrig, 2012). However, risks such as the spread of disease (Fensham et al., 2011) through corridors, or the spread of invasive species to key refuge areas for native species (McLaughlin et al., 2012) might make complete reconnection a less desirable alternative. Equally challenging, these ecological risks bring additional socio-political and economic factors (e.g., invasive species and disease can impact livestock, agriculture or humans directly) that need to be given explicit consideration when making decisions (e.g., Januchowski-Hartley et al., 2013). For example, since the mid-1970s the North American Great Lakes Fishery Commission (GLFC) has encouraged the retention and installation of low-head barriers, such as dams and weirs to both retain existing populations and minimize the spread of the invasive sea lamprey (*Petromyzon marinus*) that has caused severe ecological and socio-economic impact (e.g., lake trout fisheries).

3. Systematic planning of disconnections for conservation

As in early conservation planning initiatives, where protection was allocated to available land or based purely on opportunity, the prescription of disconnections as a conservation tool has primarily been based on ad-hoc criteria (see Fausch et al., 2009; Hayward and Kerley, 2009; Rahel, 2013 and references therein). Opportunistically allocated barriers can undermine efficiency and effectiveness of broader conservation initiatives. Optimally allocated barriers would help enhance the ecological and socio-economic benefit at large scales. For example, the cost and ecological impact of a barrier in a catchment can be minimized if planned adequately. Below we propose to use the systematic conservation planning framework (e.g., Margules and Pressey, 2000; Bottrill and Pressey, 2012) to address the allocation of barriers for the conservation of species and ecosystems (Fig. 1).

3.1. Pre-assessment: is the use of a barrier the most adequate management option?

Planners and decision makers first need to define the problem (e.g., invasive species expansion), and second identify the suite of possible solutions (e.g., use a barrier, spray, mechanical removal), including an assessment of the likely benefits and risks of installing a barrier (Fig. 1). Alternative options should be considered whenever the ecological risks and/or uncertainty in the potential outcomes of the barrier are high (Noss, 1987). If the use of a barrier as a management option is identified as suitable option to address the conservation problem, then the spatial location and allocation of resources to implement the barrier should be systematically planned (Fig. 1).

3.2. Determining optimal barrier allocation

Cost-effectiveness analysis is a corner stone of systematic conservation planning, designed to efficiently allocate limited conservation funds — thus achieving a required level of biodiversity protection (Margules and Pressey, 2000). Critical to the achievement of cost-effective conservation solutions, is setting of explicit and measurable targets, objectives or goals (Margules and Pressey, 2000), which should be established prior to undertaking the cost-effectiveness analysis. As the use of a barrier as a management tool might not benefit all species en ecosystem processes equally, and can in fact negatively impact species/processes within the study area, there is a need to evaluate the trade-offs between ecological benefits (e.g., easing threats) and impacts (e.g., interruption of ecosystem processes) for multiple species (Fig. 1, ecological component). Conducting this trade-off ensures that the placement of the barrier benefits targeted species/processes and minimizes negative impacts to other species/processes. There is also a need to explicitly trade-off ecological gains with the socio-economic costs and benefits associated with the implementation and longer-term management of barriers (Fig. 1, socio-economic component). Factors considered within the socio-economic component could include implementation and opportunity costs and benefits or other case-specific costs and benefits (see Naidoo et al., 2006). For example, implementing a barrier to minimize the spread of the invasive zebra mussel (*Dreissena polymorpha*) could also help avoid expensive economic losses (e.g., Nakano and Strayer, 2014), or the implementation of fences around protected areas could minimize the negative impact of wildlife on nearby human populations (Anthony, 2007; Packer et al., 2013).

Social and political factors can be explicitly accounted for in the trade-off of ecological and socio-economic costs and benefits as part of the evaluation of action feasibility (Fig. 2; Moon et al., 2014). In addition, the feasibility to implement a barrier can depend on the extent to which individuals, groups or communities are willing to collaborate or change, reflecting the importance of understanding influences on human behavior in achieving conservation outcomes (Fig. 1; political/policy

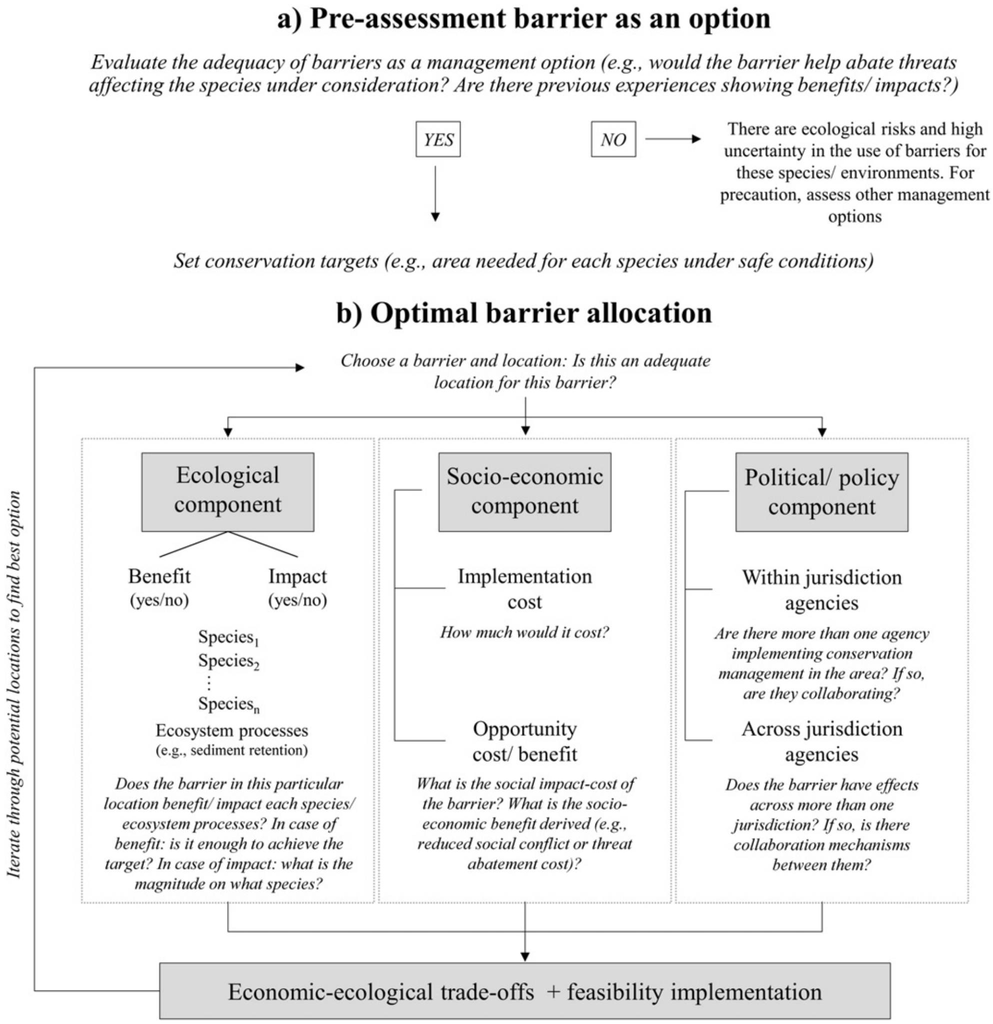

Fig. 1. Main steps of the decision-making process for optimal allocation of barriers for conservation: a) the adequacy of the barrier as a conservation option must be assessed, and b) if considered a suitable option, then its location should be optimized to maximize the ecological benefit, while minimizing the ecological impact on non-benefited species and socio-economic impacts. The feasibility of the barrier will also depend on the political context. The most optimal allocation for the barrier should be ideally chosen from all potential options.

component; see Game et al., 2011; Mills et al., 2013). For example, assessments of individual and collective readiness to engage in a conservation action can be conducted to assess interpretation of the need for the solution/s and their willingness to engage in or support action (Moon et al., 2014).

4. Demonstrating approaches to systematic planning for barriers

In Fig. 2, we draw on hypothetical scenarios to demonstrate how the systematic planning of barriers could be used to guide the spatial allocation or retention of barriers to maximize benefits, across realms, to effectively conserve native fish species and endangered mammals. In this example, if a new barrier was needed to improve conservation success of freshwater biodiversity in a catchment threatened by invasive species and loss of riparian habitats, it would ideally be placed where it would minimize impact on fish migratory pathways (so large river channels should be avoided; Jager et al., 2015) and the magnitude of revegetation and control/eradication of invasive species (Fig. 2a). Similarly, if the implementation of exclusion fences was required to protect an endangered mammal from the impact of predation by invasive species (e.g., cats on native fauna in northern Australia Frank et al., 2014), the best potential location would be in areas with healthy populations of native mammals and low densities of invasive predators. In this way we would minimize the additional cost of eradication of invasive predators from the exclusion areas and potential reinfestation risk (options 5 and 6 in Fig. 2b). Moreover the impact of these fences on other large mammals with high mobility needs should be minimized, if the extension of the barrier was large enough as to interfere with the needs of these species (Fig. 2b).

Planning for different realms independently (terrestrial, marine and fresh water) could undermine cost-effectiveness of managing ecological connectivity for conservation, because potential impacts and benefits beyond a specific realm are overlooked (Adams et al., 2013). However, integrating multiple realms in a single management plan could change the optimal spatial location of barriers recommended when planning for single realms independently (Fig. 2c). Although this integrated approach might reduce efficiency of individual management interventions it should enhance the overall efficiency, as the number and magnitude of management interventions would be optimized to achieve the same conservation objectives (Adams et al., 2013). If both conservation problems described above were addressed in same plan, a different area could be fenced for the protection of the endangered mammal and also contribute to achieve freshwater conservation goals. Although the new location for the terrestrial fence would require additional management effort to eradicate the invasive predator within the enclosed area (Fig. 2c) the fence would also benefit the freshwater biodiversity and processes. The exclusion fence for the mammal population could also help improve the condition of the catchment isolated by the freshwater barrier, by helping to reduce the impact of invasive aquatic mammals (e.g., habitat and water quality disturbance by trampling). This could,

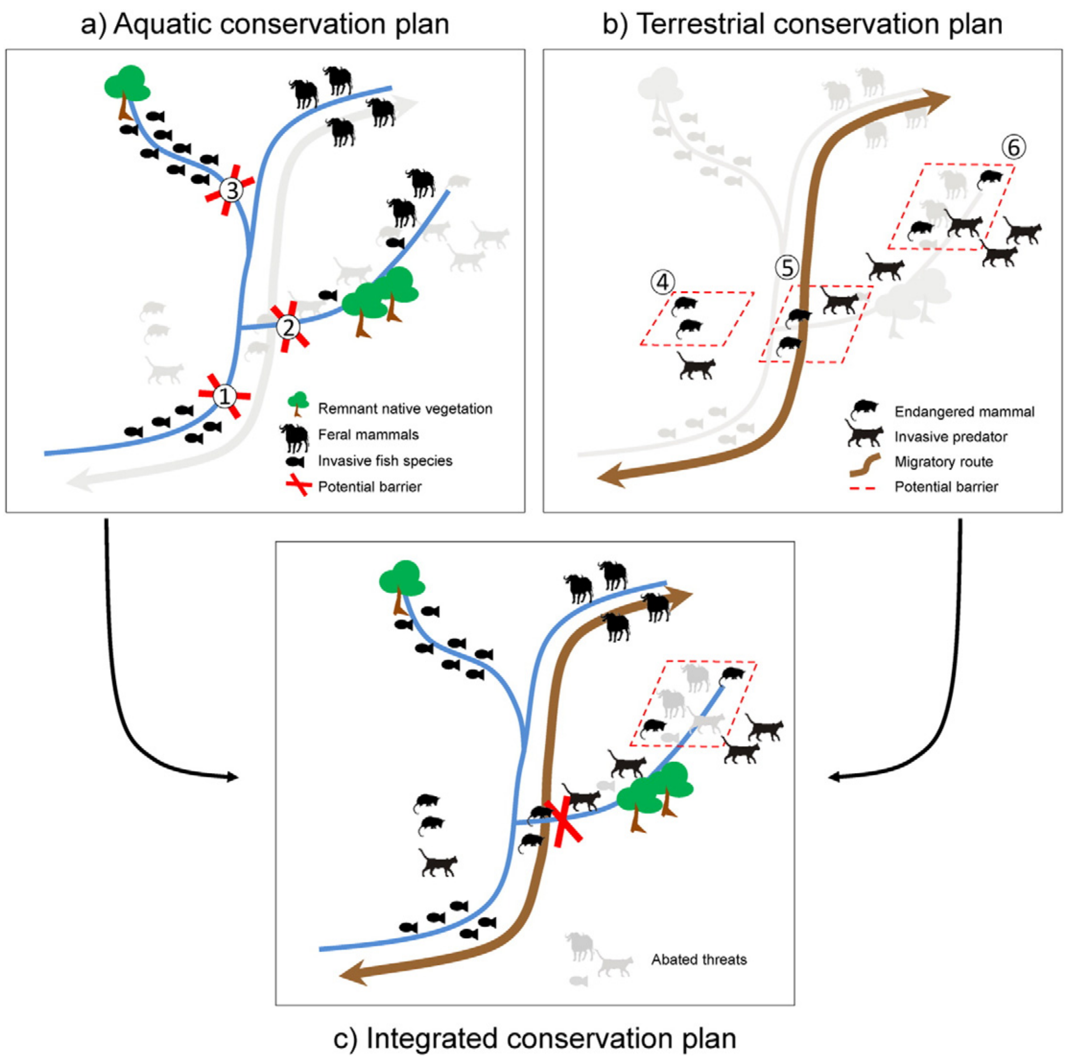

Fig. 2. Three scenarios depicting potential barrier allocation in (a) aquatic and (b) terrestrial realms, and (c) integrated allocation of barriers to benefit both aquatic and terrestrial realms. The most efficient option for the aquatic conservation plan (a) would be barrier 2 as it minimizes both the interruption of potential migrations upstream–downstream and the management effort required addressing the eradication/control of invasive species and riparian revegetation (low abundance of invasive fish above the location of barrier 2). In the case of the terrestrial conservation plan (b), barrier 4 would be the preferred option as it does not interrupt the migration pathway, minimizes the area to be fenced and the intervention required to make sure the enclosed area will be free of the invasive predator. However, when addressing both conservation problems in an integrated plan (c), the spatial allocation of some barriers might change to maximize the overall cost-effectiveness. In this case, the enclosed area for terrestrial conservation (barrier 6 in b) would also help improve the condition of the catchment upstream of the barrier for freshwater biota by facilitating the control of aquatic invasive species that disturb habitat.

for example, be the case of exclusion fences for small mammals in northern Australia (Frank et al., 2014), which could also benefit endangered populations of freshwater biodiversity constrained in isolated springs and pools (Fensham and Fairfax, 2008). The spatial allocation of barriers for one realm would then be dependent on the other realms. In this case, conservation objectives would be achieved for both realms and benefit from a common management intervention, which would also optimize for minimal cost.

5. Challenges of adequately managing disconnections for conservation

Three main challenges deserve special attention to make the use of hard and soft barriers as management tools a more suitable option for species and ecosystem conservation in the future. First, we need to better understand the effectiveness of different barriers at addressing threats and the potential effects of these barriers on the persistence of native species by interrupting key ecological processes (e.g., Vanak et al., 2010; Barrueto et al., 2014). There are many examples where the implementation of a barrier as a conservation tool did not deliver the expected benefit (e.g., Clarkson, 2004; Hoare et al., 2010). Possibly, these barriers ineffectively addressed the cause of native biodiversity decline or were aimed at the wrong cause. This is the case for the Whitaker's skink (*Cyclodina whitakeri*) in New Zealand. To conserve this reptilian species, fences were installed as a conservation tool to reduce stock grazing impacts. The construction of mammal-proof fences and eradication of mammals from the exclusion area was suggested as they identified invasive mammals as the main threat to be addressed (Hoare et al., 2010). However, after 30 years no measureable benefit was observed for skink populations, and additional assessments were undertaken to identify other possible causes for further decline.

Finally, existing conservation planning tools (e.g., Marxan or Zonation; Moilanen et al., 2009) have never been used to address the problems we present here. Therefore, new research would be needed to explore the suitability of existing tools to systematically prescribe disconnections that a) benefit the greatest number of species and b) minimize ecological impact as well as social, political and economic costs. New tools specifically designed to deal with this complex decision-making problem would also enhance our capacity to use disconnections in the future (see Ziv et al., 2012 for single realm example).

6. Conclusions

Evaluating the conservation value of barriers does and will continue to play an important role in conservation management (Packer et al., 2013; Januchowski-Hartley et al., 2013). Given increasing threats, common conservation dogmas – such as the general benefit of enhanced connectivity – must be cautiously evaluated. Creation or maintenance of barriers is recognized as a useful approach to enhance the probability of conservation success, and as we have discussed, has proven to be effective for several on-ground conservation programs. Researchers and practitioners alike need to consider novel approaches such as prescribed disconnection (e.g., Hayward and Kerley, 2009; Rahel, 2013). Prescribed disconnections could also bring socio-economic benefit by avoiding expensive losses due to the effect of invasive species (see for example Packer et al., 2013; Januchowski-Hartley et al., 2013; Nakano and Strayer, 2014). However, we still lack enough knowledge about the ecological benefit of artificially disconnecting habitats on species of conservation concern, the potential effects on the remaining community or ecological processes (Lesbarrères and Fahrig, 2012). Unfortunately, long-term monitoring programs are not the rule, which constrains our capacity to learn from the success/failure of previous experiences. Novel methods such as dynamic modeling (e.g., Brotons et al., 2012), which incorporate key ecological processes (dispersal movements and interactions with habitat quality), could help evaluate the suitability or risk associated with a barrier and ecosystem disconnection when there is an existing lack of information.

We have highlighted that new methods and tools are needed to identify the optimal allocation of new barriers, or to re-evaluate the value of existing ones, and recommend removal of not valuable ones, through the use of systematic approaches. Adequate planning and effective stakeholder engagement will enhance the effectiveness of prescribed disconnection and help minimize the undesirable effects. Ideally, the placement or retention of barriers should be planned with consideration given to all, if not as many as possible, species that could benefit or be impacted by the barrier, rather than focusing on single-species approaches as is more routinely done (e.g., salmonids or endemics plants in the aquatic and terrestrial realms respectively). Integrated planning across realms could also facilitate more efficient conservation practice, leading to enhanced success of conservation efforts and probably reduce incidence of poor performance. While the complexity of socio-ecological systems constrains the applicability of generalized conservation solutions, we argue that systematic approaches should be used to guide informed and cost-effective solutions. Our recommendations should guide the systematic evaluation and allocation of barriers to help enhance the value of this conservation tool in the face of increasing propagation of threats worldwide.

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