Planning across freshwater and terrestrial realms: co-benefits and tradeoffs between conservation actions

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Abstract

Conservation planning has historically been restricted to planning within single realms (i.e. marine, terrestrial or freshwater). Recently progress has been made in approaches for cross-realm planning which may enhance the ability to effectively manage processes that sustain biodiversity and ecosystem functions (e.g., connectivity) and thus minimize threats more efficiently. Current advances, however, have not optimally accounted for the fact that individual conservation management actions often have impacts across realms. We advance the existing cross-realm planning literature by presenting a conceptual framework for considering both co-benefits and tradeoffs between multiple realms (specifically freshwater and terrestrial). This conceptual framework is founded on a review of 1) the shared threats and management actions across realms and 2) existing literature on cross-realm planning to highlight recent research achievements and gaps. We identify current challenges and opportunities associated with the application of our framework and consider the more general prospects for cross-realm planning.

Introduction

Conservation budgets are often limited, creating the need to allocate funding for management actions in a way that maximizes conservation outcomes (Carwardine et al. 2008). Despite the critical need to allocate resources in a cost-effective manner, the potential co-benefits of different management actions for biodiversity across multiple realms (terrestrial, marine and freshwater) are rarely considered when prioritizing conservation interventions (but see Hazlitt et al. 2010; Klein et al. 2012).

Systematic conservation planning efforts began 30 years ago with applications to terrestrial and freshwater ecosystems (Kirkpatrick 1983). Subsequent studies emerged at a greater rate for the terrestrial realm than for marine (Leslie 2005) and freshwater environments (Linke et al. 2011). To ensure conservation plans are efficient, a central tenet of systematic conservation planning is complementarity (i.e., conservation areas should be selected to maximize the differences in their biotic content: Sarkar et al. 2006). This principle dictates that integration of all objectives and data should happen from the outset of the planning process (Kirkpatrick 1983; Pressey 2002). This concept has been interpreted in terms of complementary between areas, but rarely discussed in relation to complementarity of actions, particularly regarding their benefits across realms. Moilanen (2008) discussed a generalized concept of complementarity that considers the effects of actions across a landscape, including interactions between actions (different benefits and losses for different conservation features), ecological interactions between features (off-site effects), and economic interactions (cost-effectiveness). However, an in-depth exploration and operationalization across realms of a generalized concept of complementarity is lacking.

Links between realms mean that actions in one realm can affect another. As such, failure to consider these links in integrated systematic conservation planning (hereafter, *cross-realm planning*) means that planners can underestimate the effect of actions that benefit multiple realms (hereafter, *co-benefits*). Alternatively, investing in a particular action in one realm might detract from actions in another realm, or similarly, investing in a particular action might benefit one realm significantly more than another (hereafter, *tradeoffs*). Lastly, failure to plan across realms can also have undesirable and unanticipated ecological consequences (Álvarez-Romero et al. 2011; Vance-Borland et al. 2008). For example, siting marine reserves without considering land-based threats can lead to cost-ineffective spatial configurations such as investing in reservation of areas degraded by land-based pollution when alternative sites can be protected (Tallis et al. 2008). Similarly, using natural geographic boundaries such as rivers as administrative boundaries, say for national parks, fails to protect whole catchments, leaving portions open to terrestrial activities that can adversely affect river systems within or adjacent to reserves (Nel et al. 2007).

The potential co-benefits in cross-realm planning are more evident when planning for specific conservation actions (and thus considering action complementarity), as opposed to considering only generic protection such as reservation – in which case the interactions of protection between realms are less explicit (Reyers et al. 2012). For example, an action like fencing of the riparian zone to prevent cattle access can benefit riparian vegetation and associated terrestrial fauna - but also benefit aquatic systems by intercepting sediments and nutrients flowing from the land as well as providing a host of other potential benefits (Naiman and Decamps 1997; Pusey and Arthington 2003). Moreover, fencing can generate financial benefits to private business (e.g., preventing cattle from straying into, and possible getting stuck in muddy zones – Ross et al. 2011), which in turn can improve social acceptability (and cost-effectiveness) of conservation actions (hereafter, *actions*) that benefit both terrestrial and freshwater ecosystems. While examples of co-benefits are more common (e.g., Bohle et al. 2008; Robins 2002), there are examples of tradeoffs, such as the construction of artificial wetlands that likely benefit freshwater species while altering the composition of terrestrial communities (e.g., Ernst and Brooks 2003), or the use of herbicides for terrestrial weed control that have detrimental impacts on aquatic fauna (Rybicki et al. 2012).

Fully integrated cross-realm planning should thus consider the full array of ecological and socioeconomic co-benefits and tradeoffs across realms arising from any given set of actions. There has been a recent push for planning across realms (e.g., Beger et al. 2010; Stoms et al. 2005), but most studies claiming integration across realms only tangentially consider some form of influence of one realm on another (commonly threats originating in one realm and affecting another, a.k.a. cross-system threats), and rarely allocate actions for multiple realms (Álvarez-Romero et al. 2011).

The absence of truly integrated cross-realm planning is likely due to both governance and technical capability. Many jurisdictions and mandates of agencies and non-government environmental organizations are externally aligned with, or internally divided by, specific realms, inhibiting consideration of cross-realm interactions. But technical barriers to integrated cross-realm planning are substantial, related partly to limited data and understanding of cross-system threats and off-site effects of actions and partly to the capabilities of decision-support tools. Hence, our paper aims to establish a framework to further advance integration by examining two key aspects of this approach: co-benefits and tradeoffs; in doing so, we aim to provide conservation planners with information that can help them to make more cost-efficient and effective management recommendations by thinking of ways to capitalize on co-benefits and to minimize tradeoffs.

The specific objectives of this paper are to:

1) Explore potential co-benefits and tradeoffs in cross-realm planning;
2) Review literature on cross-realm planning to highlight research progress and gaps;
3) Present a conceptual framework for considering co-benefits and tradeoffs between multiple realms; and
4) Identify challenges and opportunities to advance cross-realm planning.

We focus on cross-realm integration for terrestrial and freshwater environments because this is critical for effective catchment planning and because linkages between these realms have been neglected in cross-realm studies relative to terrestrial-marine connections (Nel et al. 2009). We use a case study to illustrate our conceptual framework and exemplify co-benefits and tradeoffs associated with cross-realm planning.

Identifying co-benefits and tradeoffs in actions for freshwater and terrestrial conservation

Cross-realm planning requires an understanding of cross-realm threats, whether threats are shared across realms or arise in one and affect another. It also requires an understanding of the extent to which actions to mitigate threats propagate their benefits or adverse impacts across realms.

We expand upon the classification by Álvarez-Romero et al. (2011) of threats and stressors across realms to indicate the extent to which threats influence both terrestrial and freshwater realms. We then describe actions that can be used to mitigate each threat, indicate the extent to which each action is the same for freshwater and terrestrial planning, and assess whether the spatial location of these actions would differ if planning for each realm independently (Table 1). Lastly, we use a case study, the Daly River catchment in northern Australia, to illustrate the theoretical cross-realm planning concepts (Box 1, Figure 1, Supplementary Table 1). We selected the Daly catchment as our case study due to the breadth of data and research available for the catchment. In addition, there are a number of threats in the catchment relating to land use, invasive species, and altered fire regimes that allow us to examine a variety of concepts that are generalizable to other regions globally.

Our generic assessment (Table 1) and case study (Box 1, Figure 1, Supplementary Table 1) reveal that most anthropogenic stressors affect both terrestrial and freshwater ecosystems. For example, water extraction for agricultural and domestic use (altering groundwater and surface hydrology) directly affects the freshwater realm by altering flow regimes, thereby reducing habitat availability and modifying population dynamics of freshwater species (Chan et al. 2012). Secondary terrestrial impacts include lowering water tables with consequent death of trees. Another example is the loss of habitat for terrestrial species (e.g., birds, mammals) caused by clearing of native vegetation for agriculture. Secondary impacts on freshwater ecosystems caused by alteration of rainfall-runoff and sediment dynamics include changes to river channel morphology and declines in fish habitat availability and quality (Wood and Armitage 1997). Consequently, many actions to mitigate stressors generate at least some co-benefits.

Figure 2 illustrates the relative magnitudes of benefits for freshwater, riparian, and terrestrial ecosystems for a range of candidate actions in the Daly River catchment (based on expert opinion and peer-reviewed literature). Stressors specific to freshwater (from Table 1) can be mitigated by actions in both realms, but benefits are predominantly to freshwater ecosystems with only marginal terrestrial benefits. For example, interception of sediments and nutrients from terrestrial runoff would occur in the terrestrial realm and benefits would mostly accrue in the freshwater realm. In contrast, fire management applied in the terrestrial realm may have similar benefits across terrestrial and freshwater systems (Rieman et al. 2010) but substantially greater benefits to biodiversity and ecosystem processes within the riparian zone, which has been shown to be highly sensitive to fire (Andersen et al. 2005). Conservation actions in the riparian zone will often benefit both freshwater and terrestrial realms because riparian zones connect these two realms through ecosystem processes and cross-system threats.

Of the actions in Figure 2, most have potential socioeconomic benefits upstream or downstream of sites where actions are implemented (e.g., downstream water quality for biodiversity and human use and upstream/downstream fishing Larson et al. 2013). The relative magnitude of benefits across realms will vary between regions. For example, accrued benefits for terrestrial and riparian areas from fish passage devices can be substantial in regions where delivery of marine-derived nutrients by anadromous fish, such as salmon, is important (Hocking and Reynolds 2011).

Current progress in integrating planning across realms

Given the extent to which threats propagate across realms it is likely that cross-realm planning can deliver considerable benefits in terms of cost-efficiency and effectiveness. Our review of published conservation planning exercises that consider multiple realms revealed two sets of studies: 16 discussing theoretical principles or proposing frameworks and methods; and 48 applied studies, most of which concern marine-terrestrial links

(Supplementary Table 2). The key elements of these studies are synthesized in Table 2 and discussed below.

Advances in conservation planning theory and tools have guided siting of specific actions (e.g., reservation, restoration, natural resource management) in different realms (Ball et al. 2009; Watts et al. 2009). However, no study has optimized objectives for multiple realms. Furthermore, objectives for species or features occurring across realms are rarely considered. Approaches to integrating across realms have relied predominantly on delineation of study regions (e.g., using catchments as planning domains) and planning units that relate to ecological connections (e.g., subcatchments to facilitate consideration of downstream effects).

The most common form of integration considers cross-system threats to locate conservation areas in lower-risk regions (e.g., Linke et al. 2012a; Tallis et al. 2008). Similarly, many freshwater plans prioritize aquatic systems with higher ecological integrity, commonly assessed in relation to land uses in surrounding subcatchments (e.g., Esselman and Allan 2011; Esselman et al. 2013; Moilanen et al. 2011). Another approach considers links mediated by the movement of species between realms. For instance, Hazlitt et al. (2010) showed that considering the links to potential marine foraging habitats of the marbled murrelet's terrestrial nesting habitat influenced siting of terrestrial reserves. Klein et al. (2010; 2012) considered the benefits of land-based actions to protect coral reefs, but they did not target terrestrial and marine conservation features simultaneously. The closest to a spatially explicit integrated conservation plan is the approach by Klein et al. (In press) who evaluated the effect of terrestrial protected areas on the condition of coral reefs while also considering the contribution of terrestrial protected areas to national representative targets.

Common to all examples above is that a cross-realm perspective located actions differently to analyses that considered realms independently.

Another approach is to target conservation features across realms to explicitly conserve features in multiple connected realms. This is different to the approaches outlined above, which consider ecological processes that link realms. For example, Amis et al (2009) proposed a two-step protocol: first, determine the irreplaceability of areas for freshwater conservation, then use these data as an inverse "cost" input in the prioritization of terrestrial conservation areas, thus preferentially selecting areas where freshwater and terrestrial priorities coincide. Thieme et al (2007) locked the terrestrial reserve system into a solution for freshwater conservation priorities to achieve conservation objectives across realms. However, in these examples, the integration is not done simultaneously but after an initial single-realm assessment is complete, which does not allow for optimal allocation of actions in connected systems.

Two studies from the grey literature exemplify attempts to simultaneously prioritize terrestrial and freshwater conservation areas (TNC 2005; Vander Schaaf et al. 2006). Both planning exercises used 'vertical integration or stacking', whereby two sets of planning units are used simultaneously. Overlapping terrestrial and freshwater planning units are considered adjacent, with the link between them measured by their areal overlap. This allows a combined optimization that targets features in both realms while maximizing compactness based on adjacency within and between realms. Nonetheless, this method does not account for ecological (as opposed to areal) connectivity between terrestrial and freshwater planning units, and does not consider the potential cross-realm effects of implementing actions.

Our review draws attention to a number of practical, methodological, and theoretical limitations that have hindered past approaches to cross-realm planning. First, most studies have addressed integration partially by targeting features associated with two or more realms (e.g., diadromous fish) or by recognizing the propagation of threats across realms (e.g., land-based threats in freshwater planning). Those studies that have optimized the selection of conservation areas for more than one realm simultaneously have failed to represent ecological connections between realms and to identify the relevant actions required to address the threats across realms. In previous cross-realm planning examples, costs have been considered implicitly, by minimizing boundaries between terrestrial and marine reserves, or by considering the costs of protecting terrestrial areas to improve marine areas. Most importantly, integration studies have so far ignored the co-benefits and tradeoffs between actions across multiple realms.

A conceptual framework for cross-realm planning: linking actions to outcomes in multiple realms

Understanding how different actions could benefit multiple realms is only the first step in cross-realm planning. The critical next step is parameterizing cross-realm co-benefits (or tradeoffs) from actions. This requires constructing what we define here as an action-response curve (hereafter, *response curve*), which represents the relationship between (a) the effort allocated to an action and (b) the magnitude of the outcomes (benefits or adverse responses) across realms. Ideally response curves would be based on local measurements of responses; however, as this is unlikely to be feasible in many regions, models could be parameterized using data from a range of systems to evaluate the potential shape and magnitude of responses. Understanding the response curve for a specific action across realms reveals the potential co-benefits or tradeoffs in conservation outcomes, and in a single realm, response curves indicate what level of effort is needed to achieve a desired benefit (e.g., Murdoch et al. 2007). We extend this concept, noting that, for multiple realms, response curves can indicate what benefits in one realm might also translate into additional benefits in another realm for a given level of effort. Effort can be defined in terms of the extent of areas being managed, the amount of money being invested, the number of years for which an action is undertaken, or other spatial or temporal variables. Although the exact shape of response curves is likely to be sensitive to changes in the way in which effort is measured, we assume that the general shape (i.e. showing co-benefits or tradeoffs) is robust across specifications.

Consider two hypothetical actions that provide equal freshwater benefits but variable terrestrial benefits (Figure 3A). These curves show that the benefit (e.g., number of viable populations) per-unit-effort from two actions differs across realms. In this example, response curves are shown as linear (action 1) or logarithmic (action 2) for terrestrial species and exponential for freshwater species. If we then plot the accrued benefit to each realm for increasing levels of effort, this reveals the relationship between the terrestrial and freshwater response curves (Figure 3B). In this case, both actions have benefits in both realms (i.e. co-benefits) but benefits accrue faster for the terrestrial realm. Given the uniform freshwater response to both actions (Figure 3A), a planner can optimize outcomes across realms by implementing action 2 because it maximizes terrestrial benefits. Other forms of response curves (Figure 3C) and relationships between freshwater and terrestrial accrued benefits (Figure 3D) are likely. Once measured, response curves can be interpreted by planners to explore the potential outcomes and cost-efficiencies of candidate actions at different levels of effort across realms.

Responses to a given action can be: positive in both realms; positive in one realm and negligible (either positive or negative) in the other; or positive in one realm, but negative in the other. Therefore, response curves could reveal either co-benefits or tradeoffs (Figure 4), and will take on a variety of shapes depending on the context in which the action is applied.

For co-benefit outcomes we show three types of curves (Figure 4, top right), focusing only on environmental benefits for simplicity, although the concepts could translate easily to socioeconomic benefits. For type 1 curves, benefits accrue faster for freshwater than terrestrial realms; for type 2, benefits accrue at the same rate for both realms; and, for type 3, benefits accrue faster for terrestrial than freshwater realms.

An example of a type 1 response is the restoration of a river channel through reduced erosion, which will likely have more immediate benefits for aquatic than terrestrial organisms (Wood and Armitage 1997). The ecological benefits of controlling some invasive species (e.g., controlling weeds that impact riparian zones such as Andropogon gayanus, Petty et al. 2012) could have comparable benefits in the freshwater and terrestrial realms (type 2 response) via restoring the structure and composition of riparian biota, thus maintaining natural nutrient cycling and fire regimes. A type 3 response would be improved fire management with benefits to the terrestrial realm (e.g., maintenance of ecosystem processes within the riparian zone, which has been shown to be highly sensitive to fire) accruing faster than for freshwater (e.g., decreased inputs of sediments and nutrients associated with erosion of burned areas). Further examples of potential co-benefit outcomes are provided in Box 1 regarding our case study.

Challenges to planning and implementing conservation actions across terrestrial and freshwater realms

The main challenges to planning across freshwater and terrestrial realms include a lack of critical information concerning ecological linkages, benefits, off-site effects, and cost-effectiveness of different actions across realms. In addition, practical challenges to implementing actions can arise due to a historical tendency to manage these two realms separately.

Cross-realm planning cannot be achieved without spatially-explicit data on the linkages between realms, including the origin, extent, and magnitude of cross-system threats and ecological interdependencies. Furthermore, an understanding of these threats should be accompanied by a description of how the systems respond both to the threat and management action to mitigate the threat (benefits).

Benefits of actions can be measured in terms of changes in probabilities of persistence (e.g., Carwardine et al. 2011), population sizes, or changes in extent or “condition” of features in each realm. Benefits can be either estimated directly (e.g., through experimental or observational data on species/ecosystem responses to threats and actions to mitigate these threats) or by expert knowledge if empirical data are lacking. However, as benefits are likely to be context-dependent, estimation is a non-trivial exercise. For example, if several areas are connected physically or biologically, then implementation of an action could result in off-site benefits that result in a total benefit much greater than if the action were implemented in places with less connectivity (Hermoso et al. 2012). Long-term monitoring and evaluation of management actions can provide data on ecological responses, but both activities need to occur across realms to detect potential benefits accrued beyond the realm in which actions are undertaken directly.

Ideally, full response curves will be parameterized, allowing for explicit consideration of what objectives can be achieved under different levels of effort or constrained budgets. At a minimum, both costs and benefits should be estimated for a single point on a response curve for each realm which would allow integrated planning for one level of effort (Figure 3).

Developing response curves requires information about conservation costs (typically categorized as acquisition, management, transaction, damage, and opportunity costs). Like estimates of benefits, estimates of the financial cost of 'an action' might seem easy, but context also complicates the estimation process. For example, there might be economies of scale, meaning that it can be cheaper to apply an action across a larger area than a smaller one (Adams et al. 2012). Similarly, if dealing with on-farm conservation activities, the costs of applying a particular action are likely to depend, interactively, on other (market-focused) activities on the farm, producing synergies between production and conservation outcomes (e.g., Peerlings and Polman 2004). Adams et al. (2012) showed the coincidence between threats to land production and threats to natural values in the Daly River catchment, and hence the extent to which land management and conservation activities have co-benefits. For example, fire management has direct financial benefits to graziers and other agriculturalists (Ross et al. 2011) and can also deliver social and environmental benefits (Fitzsimons et al. 2012). Likewise, many weeds cause significant productivity problems, so their control is often welcomed by agriculturalists (Pimentel et al. 2005; Sinden et al. 2004). Fish passages are likely to benefit recreational and traditional fishers, with possible knock-on benefits for tourism (Carson and Schmallegger 2009).

One way of dealing with complex co-benefits or tradeoffs is to estimate complex cost functions that, in essence, net out other socio-economic impacts when estimating the cost of specific actions; another approach would be to treat the socioeconomic system as another realm – extending our proposed response curves to incorporate additional side-effects of actions, or to consider other types of actions. This would, for example, make explicit the effects of controlling feral animals (e.g., pigs, water buffalo) to benefit many aquatic and terrestrial species, but also potentially detracting from indigenous livelihoods (for which these species can be an important food source; Robinson and Wallington 2012).

An estimate for a single point on the response curve can be used in existing systematic conservation software, such as Marxan with Zones (Watts et al. 2009) or Zonation (Moilanen et al. 2011) to provide potential sets of priority actions in planning units that most cost-efficiently achieve benefits to conservation features. Unfortunately, existing software cannot currently take advantage of continuous benefit functions (response curves), so purpose-built optimization tools are needed. These tools should not only be able to use those continuous functions, but also integrate interactions between management actions (additive, synergistic, or antagonistic) in a spatially-explicit context to better account for connectivity requirements. Uncertainties around the response curves could also be characterized (e.g., using methods detailed by Speirs-Bridge et al. 2010) and sensitivity analyses undertaken to assess the reliability of planning outputs and the potential implications of different conservation decisions based on limited data (Burgman et al. 2005; Regan et al. 2005).

A better scientific understanding of cross-realm planning will ensure limited conservation budgets are allocated more efficiently only if managers and policy makers can reduce the compartmentalization of planning and actions within realms. Current constraints imposed by highly-specified funding streams and reporting requirements for single-realm conservation (e.g., revegetation, fire management, or feral animal control programs exclusively targeting terrestrial ecosystems) will need to be overcome to realize the substantial benefits to be gained from conservation across realms. This could be facilitated partly by enhanced collaboration among natural resource management agencies that are commonly isolated (e.g., fisheries, water management, environment), by supporting catchment management authorities to explicitly design actions across realms, and by providing dedicated funding streams for cross-realm planning (e.g., integrated catchment management). There are promising signs in this direction. One example is the series of water quality improvement plans by catchment management bodies in the drainages of the Great Barrier Reef (Australia), now beginning to reduce sediment and nutrients flowing into the Reef's lagoon (Brodie and Waterhouse 2012). Another example is the Cedar River Municipal Watershed Aquatic Restoration Plan (USA), which identifies areas where co-benefits of restoration actions can be obtained for aquatic, riparian, and terrestrial ecosystems (Bohle et al. 2008). However, better planning is needed to integrate actions that address objectives other than water quality and to explore co-benefits and tradeoffs related to ecosystem services (e.g., carbon retention and sequestration). Furthermore, natural resource managers need best-practice guidance on the potential benefits of commonly-implemented management actions, such as weed and fire control, for multiple realms and how these might be applied to more effectively achieve multiple objectives across realms.

Conclusions

Existing examples of cross-realm planning have not explicitly estimated the potential benefits of actions to multiple realms. We have identified three key technical steps toward planning more effectively and efficiently across realms:

1. Qualitatively assess the existing threats to each realm, the actions to mitigate those threats, and the extent to which these threats and actions are similar or dissimilar and propagate their effects across realms;
2. Construct action-response curves for actions under consideration, related to explicit objectives. If data are not available to develop whole curves, it will be necessary to identify at least one point on each curve related to a specific level of response;
3. Use existing or purpose-built software to optimize the allocation of actions spatially, according to the distribution of threats, conservation features, and the expected co-benefits or tradeoffs accruing to each realm based on the response curves, considering also socioeconomic costs and benefits, if possible.

Crucially, the conservation benefits arising from these technical advances will be realized only if governance arrangements are also made more amenable to cross-realm planning. Approaches are being developed to review the adequacy of governance against broad environmental outcomes (e.g., Dale et al. 2013) and these can be adapted to planning across realms; but some broad requirements are already obvious. One is to strengthen collaborations among agencies and funding streams currently tasked with realm-specific management, identifying and removing constraints on effective cross-realm operations. A second is to maintain the financial support to organizations such as catchment management authorities that were established explicitly for cross-realm planning, building sustained capacity within these groups to use, adapt, and help design technical methods for integrating terrestrial and freshwater actions. A third requirement is to adapt existing institutions or build new ones to manage the equitable sharing of the benefits and costs (environmental, financial, and social) of cross-realm planning, recognizing that actions applied in one place, possibly requiring extractive activities to be curtailed, will often yield benefits in different places.

We know that realms are linked physically, biologically, socially and economically, and that actions in one realm invariably affect others. Until we are better at accounting for interactions across realms, our planning and conservation actions will be less cost-effective than they could be. Data deficiencies will clearly prevent the construction of accurate models of cross-realm interactions in the short-term, but progress can be made with the technical steps above. Following these steps will make explicit the assumptions and understanding that are presently implicit or absent, and the resulting models will have heuristic value through being scrutinized and challenged. Ultimately, success will depend on adapting governance structures, and this will require high-level commitment to integrated management, adequate funding, and reform of sometimes entrenched power structures.

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Box 1 Case study of the Daly River catchment, Northern Territory, Australia. We use the Daly River catchment in the Northern Territory (Figure 1) to illustrate cross-realm planning concepts. Many of the catchment's conservation values are related to riparian zones, aquatic systems (e.g., rivers, floodplain wetlands, springs, estuary), and the biodiversity they support. The land and water systems of the Daly also sustain important cultural, spiritual, and socioeconomic activities for indigenous and non- indigenous people (Jackson et al. 2012; Stoeckl et al. 2013). The catchment is recognized nationally and internationally for its high ecological value. The estuary and lower floodplains meet criteria related to waterbirds for listing as a Ramsar Wetland of International Importance. The river is almost unique in northern Australia in having strong perennial flows, with associated significance for aquatic flora and fauna. The middle and upper parts of the catchment contain national parks and indigenous protected areas. The diversity of ecological and socioeconomic values has led to substantial research effort invested in defining conservation and management priorities for the freshwater systems in the Daly (Hermoso and Kennard 2012; Hermoso et al. 2012; Linke et al. 2012b).

Despite existing protection (Figure 1) and relatively low levels of clearing (~5%), native species are threatened by changes in fire regimes, degradation of riparian zones, expanding weed infestations, and invasive animals (Supplementary Table 1). These threats affect both freshwater and terrestrial ecosystems, so many of our recommended conservation actions are the same for both realms. However, the effects of an individual action could be substantially different for each realm, resulting in different types of action-response curves (Figures 3,4). For example, consider a potential action to reduce grazing. Grazing has been implicated in reduced native vegetation cover and subsequent loss of bird and mammal biodiversity in the

Daly River catchment (Franklin et al. 2005; Woinarski et al. 2011). Reduced grazing will therefore directly benefit terrestrial ecosystems while benefits to freshwater ecosystems will be indirect (e.g., reduced sedimentation), accrue over longer periods, and be discernible only for more extensive intervention. Hypothetically, grazing could have a linear benefit-to-effort relationship on land but an exponential one for fresh water (Figure 3B, Figure 4). Importantly, while reducing cattle density in any paddock will generally have a positive environmental impact, it does not necessarily require a direct reduction in profits, for example when reproductive rate increases in a smaller herd (Burns et al. 2010). Up to a point, overall productivity can therefore be maintained with lower stocking rates.

Other responses to management actions in the Daly include water control (type 1, Figure 4) and control of introduced cane toads (type 2, Figure 4). The restriction of water extraction in the Daly River (Chan et al. 2012; Stoeckl et al. 2013) will likely have more immediate benefits to aquatic organisms, for example through increased habitat availability, than to riparian and terrestrial biota for which benefits of the management action might take longer to accrue (Arthington and Pusey 2003; Chan et al. 2012). In contrast, the ecological benefits of controlling cane toads might show similarly rapid benefits for species in diverse ecosystems: aquatic (e.g., fish), semi-aquatic (e.g., frogs, crocodiles), and terrestrial (e.g., monitors, snakes, birds, and predatory mammals such as quolls). In all cases, control reduces the consumption of poisonous eggs, tadpoles, and adult toads (Shanmuganathan et al. 2010).

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Figure 1 The Daly River catchment. The catchment extends over approximately 5.2 million ha, from the coastline south-west of Darwin to 250 km inland. The inset panel shows the Northern Territory in white and the catchment in black. Land uses (ABARES 2010) and streams are shown in the main map. Approximately 10% of the catchment is covered by national parks, such as Nitmiluk Gorge in the northeast, and Indigenous protected areas, such as Fish River in the northwest.

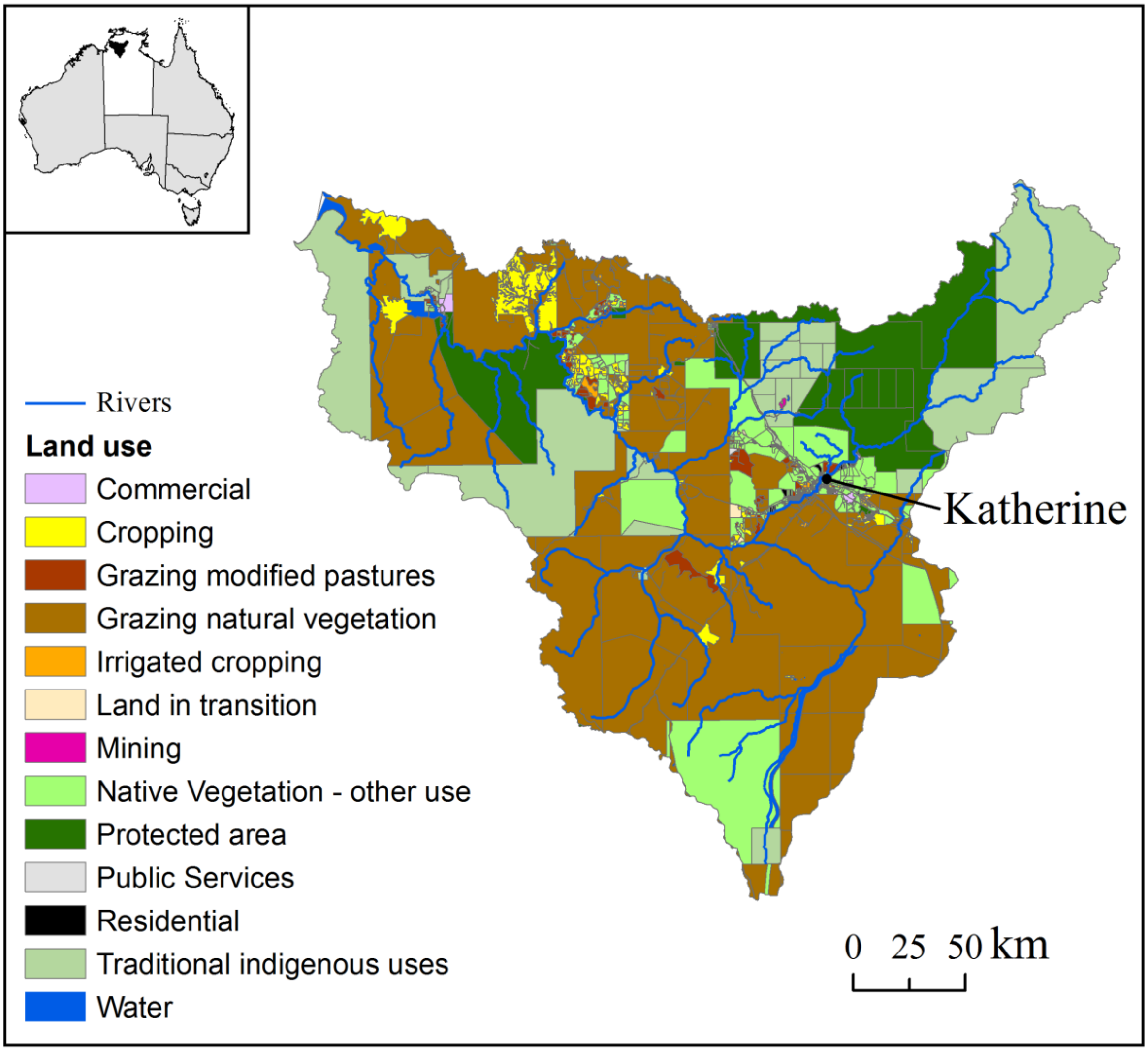

Figure 2 Examples of conservation actions and the propagation of benefits across terrestrial and freshwater realms. We consider the riparian zone as an interface between both realms where actions can be implemented and benefits accrued. Rows indicate where the action occurs and columns indicate where benefits are accrued. The relative height of polygons indicates the relative magnitude of benefits in the three types of ecosystem.

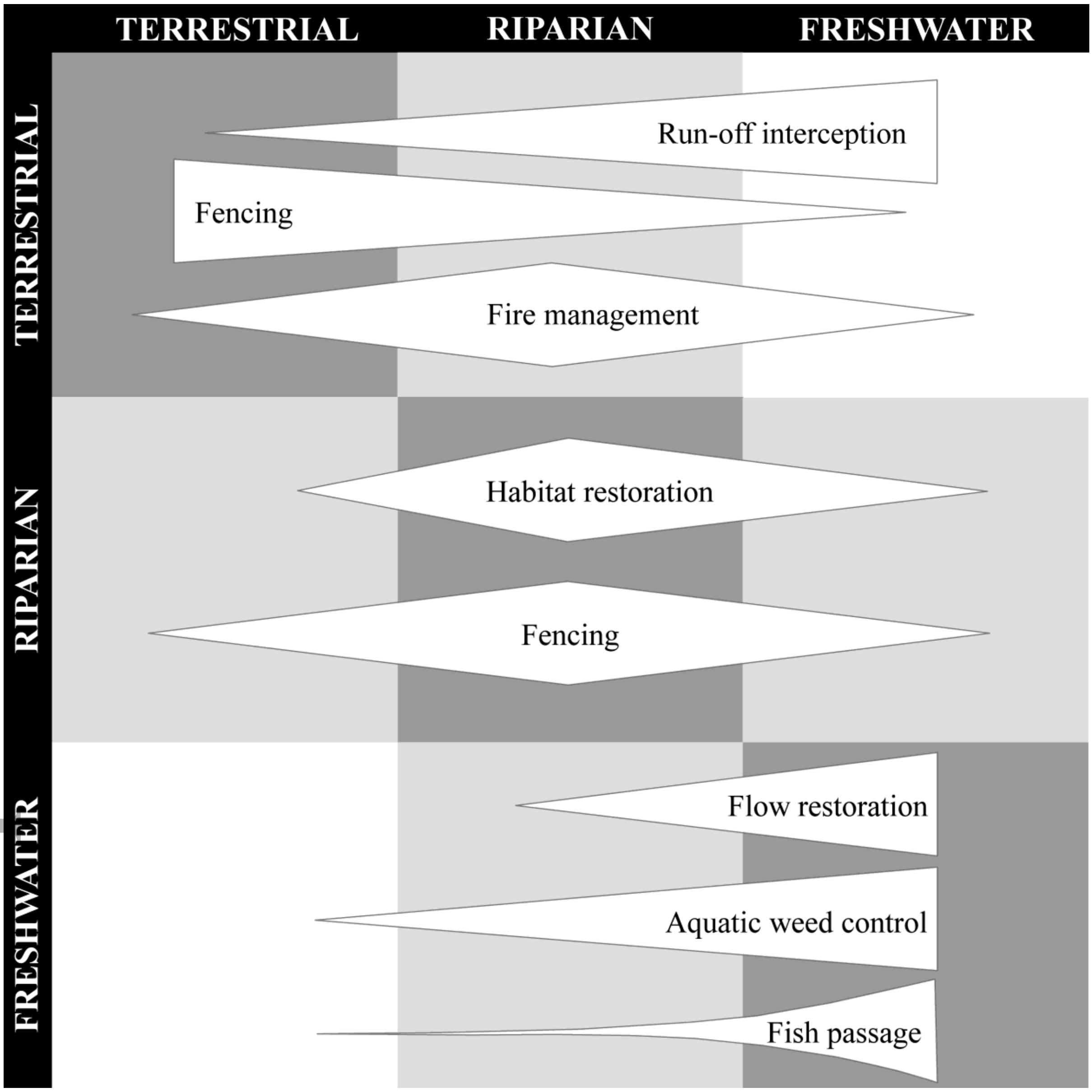

Figure 3 Examples of response curves. The first column shows typical response curves. These indicate the incremental benefits (e.g., number of viable or safeguarded species/populations/ecosystems) corresponding to per-unit increments of effort (e.g., area managed, number of years managed) for two actions with variable terrestrial benefits (‘1’ and ‘2’) and equal freshwater benefits. The second column shows the accrued benefit associated with each action (‘1’ and ‘2’) for freshwater versus terrestrial realms. (A) The incremental benefits for two actions with variable terrestrial benefits (‘1’=linear response and ‘2’=logarithmic response) and equal freshwater benefits (exponential). (B) For the same two actions as in (A), the accrued benefit associated with each action (‘1’ and ‘2’) for freshwater versus terrestrial realms (type 3 relationship, Figure 4). (C) The incremental benefits for two actions with variable terrestrial benefits (‘1’=linear response and ‘2’=logarithmic response) and equal freshwater benefits (logarithmic with higher per-unit benefits than Terrestrial 2). (D) For the same two actions as in (C), the accrued benefit associated with each action (‘1’ and ‘2’) for freshwater versus terrestrial realms (type 1 relationship, Figure 4). In both cases (B and D) we observe co-benefits, where accrued benefits for the terrestrial realm will be higher if action 2 is implemented, but freshwater benefits will be notably higher at medium and high levels of effort for
(B) compared to rapidly accrued freshwater benefits for low levels of effort for (D).

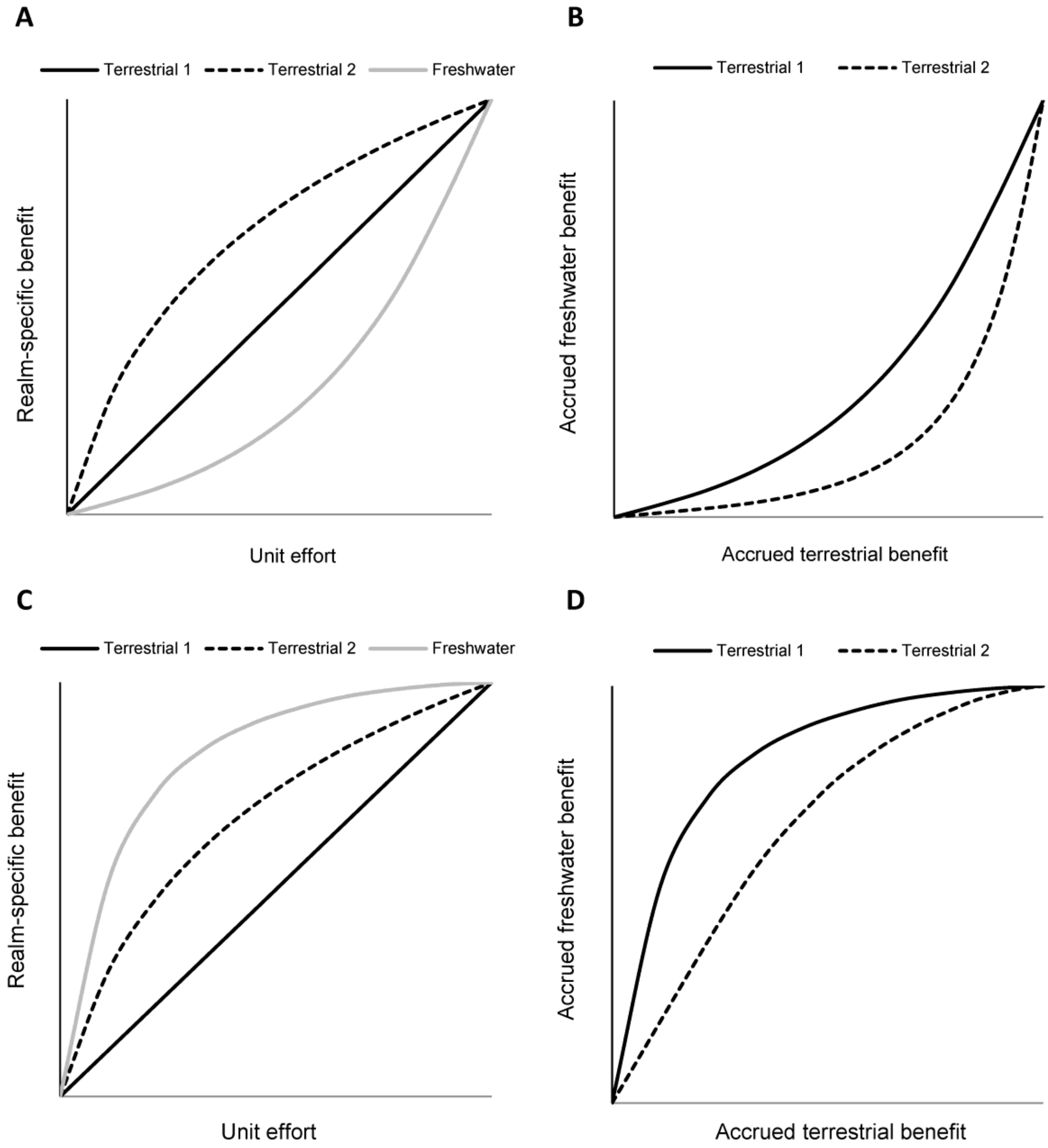
A
Terrestrial 1
Terrestrial 2
Freshwater
Realm-specific benefit
Unit effort
B
Terrestrial 1
Terrestrial 2
Accrued freshwater benefit
Accrued terrestrial benefit
C
Terrestrial 1
Terrestrial 2
Freshwater
Realm-specific benefit
Unit effort
D
Terrestrial 1
Terrestrial 2
Accrued freshwater benefit
Accrued terrestrial benefit

Figure 4 Examples of curves describing actions targeting one realm that provide co-benefits with (top right) or involve tradeoffs between (top left and bottom right) responses in the other realm. An action is ineffective if it has negative responses in both terrestrial and freshwater realms. The shapes of the curves denote variation in the magnitude of responses to different levels of effort for a given management action. Type 1 = the response to a management action increases faster in the freshwater realm than in the terrestrial realm; Type 2 = the response to a management action increases at the same rate in the freshwater realm as in the terrestrial realm; Type 3 = the response to a management action increases faster in the terrestrial realm than in the freshwater realm.

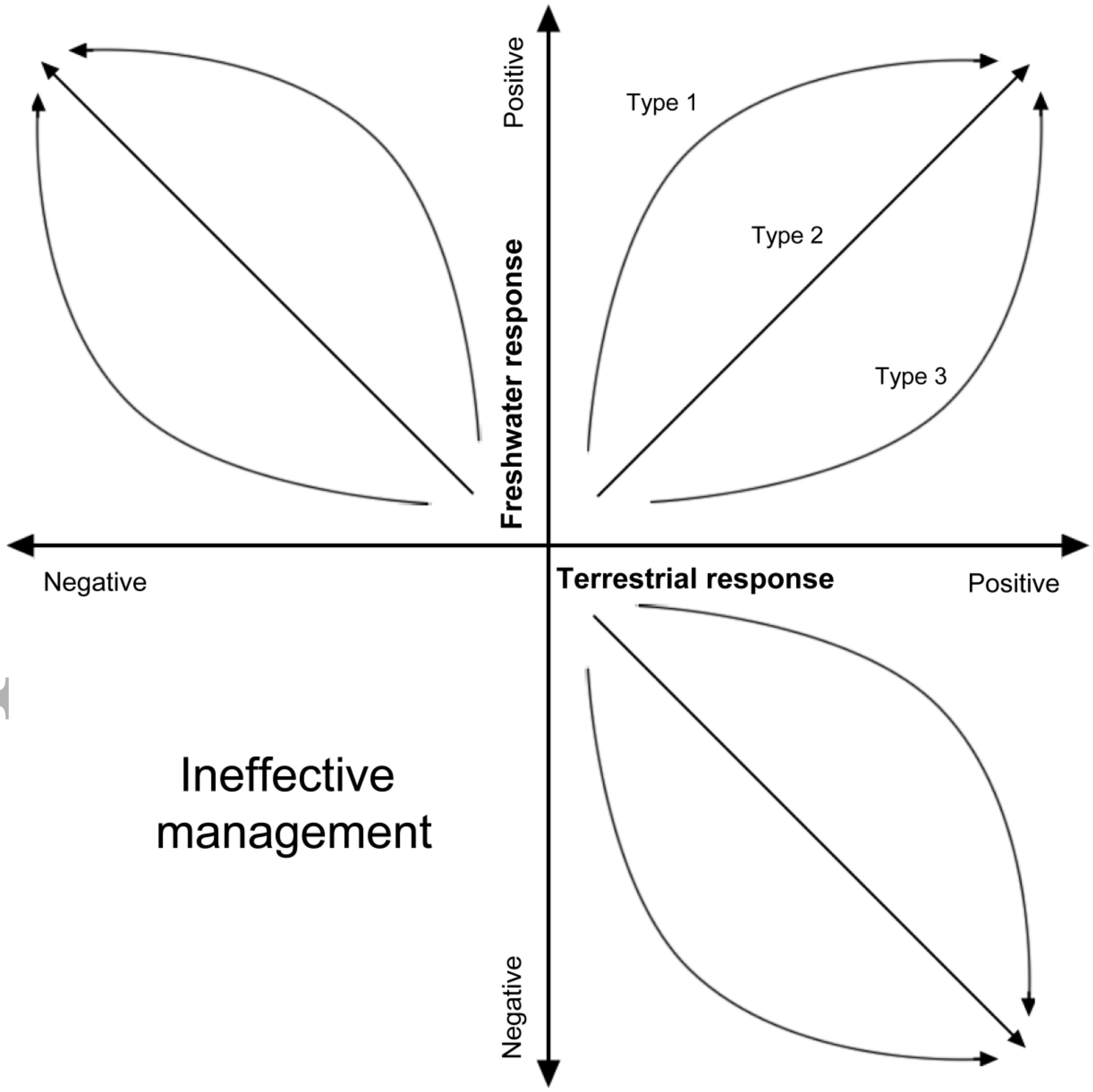

Table 1 Examples of threats to freshwater and terrestrial systems, candidate management actions, and the similarities in management actions across realms. Our classification of threats is expanded from Álvarez-Romero et al. (2011) and candidate management actions are expanded from Salafsky et al. (2008). For each threat we list the associated stressor[1] and indicate to which realm the stressor applies (freshwater/terrestrial, just freshwater or just terrestrial). For each threat we also provide candidate management actions[2] and indicate the realm that each action is applicable to. Where a candidate management action is applicable to both terrestrial and freshwater realms we indicate the extent to which each action is similar across realms: * indicates that it is the same action and location for both realms and # indicates that it is the same action but would likely be implemented in a different spatial location for each realm.

Threat	**Stressor**	**Candidate management actions**
Land Use		
Urbanization		
Terrestrial/Freshwater	TC, G/SW	*toxicant interception/mitigation #land use planning, restoration of habitats
Freshwater	N	nutrient interception/mitigation
Agriculture		
Terrestrial/Freshwater	TC, E	*toxicant interception/mitigation #land use planning, restoration of habitats
Freshwater	N, S	nutrient interception/mitigation, sediment removal
Grazing		
Terrestrial/Freshwater	E, S	#fencing
Terrestrial		sustainable grazing
Mining		
Terrestrial/Freshwater	TC	*toxicant interception/ mitigation #restoration of habitat
Freshwater	S	sediment removal
Forestry		
Terrestrial/Freshwater	TC, E	#restoration of habitat, land use planning
Freshwater	N, S	nutrient interception/mitigation, sediment removal

Roads and transport corridors		
Terrestrial/Freshwater	E, RPS, FV, TC, S	*toxicant interception/ mitigation #restoration of habitat, land use planning
Freshwater	FC, N	restoration of freshwater connectivity
Biological Resource Use		
Hunting		
Terrestrial/Freshwater	RPS	*regulation/enforcement
Fishing of aquatic resources		
Freshwater	RPS	fisheries regulation/enforcement
Natural System Modification		
Fire and fire suppression		
Terrestrial/Freshwater	E, NC	*fire management
Freshwater	S	
Riparian degradation		
Terrestrial/Freshwater	N, S, E, NC, WF, SH, HS, OM	*restoration of habitats, fencing, fire management, weed management
Dams and water use		
Freshwater	FC, WF, GW	restoration of freshwater connectivity, environmental flow allocations, restrictions on extraction of ground water
Invasive non-native alien species		
Invasive non-native plants		
Terrestrial/Freshwater	NC	#weed management
Freshwater	WF	weed management
Invasive non-native animals		
Terrestrial/Freshwater	E, RPS, FV	#feral animal control
Climate Change		

Sea Level Rise		
Terrestrial/Freshwater	SA, NC, RPS, FV, FC	*tidal barrages and levee banks
Altered rainfall regimes		
Terrestrial/Freshwater	NC, WF, RPS, FV, E, FC	#protection of existing refugia
Freshwater		environmental flow allocations
Altered temperature regimes		
Terrestrial/Freshwater	NC, WF, RPS, FV	#Protection of existing refugia

1 Stressor codes: TC = toxic chemicals, G/SW = garbage/solid waste, N=nutrients, S=sediment, E=Erosion, NC=changed nutrient cycling and energy transfer, WF=altered water flow, GW=altered ground water surface water connections, RPS= reduced population size, FV=fragmentation of vegetation, FC = fragmentation of aquatic connectivity, SH=loss of shading, HS=loss of coarse wood as habitat structure, OM= loss of allochthonous organic matter, SA=increased salinity

2 management activity descriptions: *toxicant interception/mitigation* - activities include installation of mechanical devices to intercept toxic chemicals such as petrochemicals and herbicides and education and enforcement to ensure their appropriate use and disposal; *land use planning* – spatial zoning or planning of land uses to minimize or relocate impacts to realms; *restoration of habitats* – activities such as revegetation to improve habitat quality and quantity; *nutrient interception/mitigation* - activities include construction of artificial wetlands to intercept nutrients and education and enforcement to ensure appropriate use of fertilizers; *sediment removal* – dredging, use of sediment traps and erosion control activities on farms; *fencing* – use of barriers such as fences to prevent stock access to sensitive ecosystems (e.g., riparian zones); *sustainable grazing* – best practice grazing management to minimize ecosystem impacts such as reduced stocking rates, rotating stock or maintaining a percentage vegetation cover through approaches like cell grazing; *restoration of freshwater connectivity* – removal of barriers (i.e. dams, weirs, road culverts and other structures) or installation of fishways (e.g., rockramps, fish ladders/locks/lifts); *regulation/enforcement* – education regarding existing regulations or creation of new policies/regulations and enforcement of these through fines; *fire management* – fire management planning including placement of fire breaks, areas to remove fuel load and approaches to seasonal burning; *environmental flow allocations* – flow restoration by releasing water from dam or restricting extraction or interception of surface water to maintain environmental flows; *restrictions on extraction of ground water* – using regulation such as water allocations or plan to restrict the total amount of ground water extracted; *weed management* –chemical application, biocontrol or manual removal; *feral animal control* – shooting, poisoning, trapping, biocontrol; *tidal barrages and levee banks* – creation of barriers or infrastructure to inhibit salt water intrusion; *protection of existing refugia* – identification and protection through reserves of climatic refugia for sensitive species.

Table 2 Key elements of planning exercises considering cross-realm integration and examples of the range of approaches used in their application. This table extends the study by Álvarez-Romero et al. (2011) by adding 22 studies (mostly regarding terrestrial-freshwater integration, plus some recent terrestrial-marine applications). Further detail is available in Supplementary Table 2.

	Combinations of realms		
Key element	**Terrestrial-Freshwater (16)**	**Marine-Terrestrial (22)**	**Terrestrial-Freshwater-Marine (10)**
Objectives/targeted features	Focus on freshwater-dependent biodiversity (macroinvertebrates, fish, turtles, waterbirds), ecosystem types (rivers, lakes, wetlands) or refugia. Some studies targeted terrestrial biodiversity (vegetation types, species) or had a terrestrial focus using catchments as the spatial context.	Focus on marine biodiversity, although some studies targeted terrestrial biodiversity, nesting habitats for seabirds, intertidal ecosystems, and adjacent features in the littoral zone. More typical targets included nearshore coastal areas (bays and estuaries, coastal buffers), diadromous and estuarine species, marine ecosystems, water quality regimes, marine/terrestrial habitat for marine species, and coral reefs.	Commonly, objectives were independently set for terrestrial, freshwater and marine biodiversity. Some planning exercises also targeted estuaries and rivers, diadromous species, waterbirds, and coastal species and ecosystems.
Planning domain	Commonly used drainage basins, but some studies used management units (e.g., water management areas) or political boundaries (e.g., provinces) - sometimes aligned to ecogeographic regions and catchments.	Commonly ecoregional boundaries (terrestrial and marine), but some studies used management or political boundaries. Additional criteria were intertidal zones/coastal interfaces and habitats (coastal forests, mangroves, reefs, estuaries), national parks, bathymetry, and nesting and marine feeding areas of seabirds.	A combination of the previous two integration approaches, commonly based on ecoregional boundaries, catchments, and bathymetry.
Planning units	Mostly freshwater: subcatchments, stream/river reaches, but some studies also included terrestrial units (hexagons).	Commonly uniform units (hexagons, squares) across marine or both realms, but sometimes different sizes in each realm). Other units included: linear units along the land-sea interface, bays and estuaries (delimited by catchment boundaries), subcatchments, habitats (coral reefs), and combinations thereof.	Similar to terrestrial/marine plans: mostly uniform units (hexagons) or linear units for the land-sea interface. Freshwater parts of study domains were subdivided into subcatchments or streams/reaches.
Ecological processes and interactions	Not considered in some studies, and implicit in others (e.g., incidental buffering of wetlands through terrestrial	Not considered in some studies. Otherwise, targeting species and oceanographic processes relevant to	Targeting diadromous species to maintain links between realms (e.g., salmon runs delivering nutrients to

	protection). Explicit coverage included: movements of waterbirds and turtles across catchments (not restricted to waterways), longitudinal connectivity along waterways relevant for terrestrial species, and estuaries identified as priorities for catchment-estuarine processes.	delivery of marine-derived nutrients to terrestrial ecosystems (e.g., salmon runs, seabirds), maintenance of nutrient/sediment input to coastal ecosystems through rivers, targeting interface habitats (e.g., wetlands, mangroves), nesting areas, terrestrial and marine habitats of species, targeting upper catchment to maintain water quality, and use of streams as corridors.	freshwater ecosystems directly and influencing riparian vegetation) and interface habitats (e.g., mangroves, estuaries).
Cross-system threats	Where spatially explicit (not in all studies): land use as a surrogate for ecological integrity/condition (based on surrounding catchment land use, population density, roads, agriculture, grazing, fires, weeds), point sources of pollution, and scheduling of conservation actions (including freshwater features) based on vulnerability (including land-based threats).	Considered indirectly in some studies as presence of urban areas, roads and industry as proxies for socioeconomic cost of conservation. Where spatially explicit: land use to assess integrity of interface, land-based threats used to prioritize conservation areas, avoidance of land-based threats (e.g., aquaculture, nutrient and organic runoff) or assessment of habitat (e.g., coral reefs) condition using river plume models.	Similar to the previous exercises, plus additional assessments, including dam density and coastal modifications.
Integration approach	Sequential (e.g., freshwater priorities reduced “cost” when selecting terrestrial priorities, or terrestrial reserves identified first, then locked in for freshwater prioritization), areas prioritized if less affected by land-based threat, longitudinal propagation of land-based threats, minimizing selection of high economic values, including inter-subcatchment longitudinal connections in optimization, use of subcatchments to achieve integrity/function and preferentially grouping subcatchments along waterways (as corridors), riparian areas and groundwater recharge zones, aggregating adjacent or overlapping planning units of independent prioritizations.	Simultaneous selection of features across both realms, higher costs of areas adjacent to urban, roads and industry, design criteria (including whole bays, estuaries, coastal catchments, adjacency to conserved and protected terrestrial areas), avoiding imminent land-based threats, maximizing return on investment (ROI) by selecting either land-based or marine-based actions, maximizing coral reef condition by protecting forests, connecting selected conservation areas to include marine processes.	Integration of terrestrial and freshwater conservation areas by using different units but quantifying adjacency based on areal overlap, sequential selection (e.g., marine sites added to include areas where high-priority terrestrial and marine sites are ecologically connected), concurrent and post hoc integration, design criteria used by experts to delineate priority conservation areas (e.g., select areas with better water quality and adjacent to well-preserved forested areas).
Actions with cross-realm effects	Not considered in most studies. Some studies considered only generic protection. A few land-based actions included reducing direct livestock access to waterways, restoring riparian vegetation cover to increase shading and to reduce sediment and nutrient	Not considered in most studies. Protection of forests to avoid nutrient/sediment runoff, protecting marine habitat to ensure viability of species occupying both realms or to maintain input of marine-derived nutrients to terrestrial systems.	Not considered in most studies. Similar to the previous two approaches.

	inputs, use of 5 m riparian protection zones or setbacks either side of all streams.	