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Prioritizing management actions for the conservation of freshwater biodiversity under changing climate and land-cover

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ABSTRACT

Freshwater ecosystems are declining under climate change and land-use change. To maximize the return on investment in freshwater conservation with limited financial resources, managers must prioritize management actions that are most cost-effective. However, little is known about what these priorities may be under the combined effects of climate and land-cover change. We present a novel decision-making framework for prioritizing conservation resources to different management actions for the conservation of freshwater biodiversity. The approach is novel in that it has the ability to model interactions, rank management options for dealing with conservation threats from climate and land-cover change, and integrate empirical data with expert knowledge. We illustrate the approach using a case study in South East Queensland (SEQ), Australia under climate change, land-cover change and their combined effects. Our results show that the explicit inclusion of multiple threats and costs results in quite different priorities than when costs and interactions are ignored. When costs are not considered, stream and riparian restoration, as a single management strategy, provides the greatest overall protection of macroinvertebrate and fish richness in rural and urban areas of SEQ in response to climate change and/or urban growth. Whereas, when costs are considered, farm/land management with stream and riparian restoration are the most cost-effective strategies for macroinvertebrate and fish conservation. Our findings support riparian restoration as the most effective adaptation strategy to climate change and urban development, but because it is expensive it may often not be the most cost-efficient strategy. Our approach allows for these decisions to be evaluated explicitly.

1. Introduction

Pressures on ecosystems worldwide outpace current resources available for their management. As a result, prioritization of resources is necessary to maximize the benefits of conservation outcomes (Bottrill et al., 2008; Joseph et al., 2009). A common mistake in priority setting for conservation is the focus on prioritizing species, habitats, or locations rather than management actions (Game et al., 2013). However, it is the actions aimed at saving species and habitats that use the resources of conservation agencies, not the species or habitats themselves. Encouragingly, progress is being made in the development of prioritization assessments that account for the costs of actions, their benefits, and likelihood of success (Carwardine et al., 2012; Hermoso et al., 2012; Turak and Linke, 2010; Wilson et al., 2007). Another shortcoming of current prioritizations is that few studies account for multiple interacting threats when prioritizing management actions for conservation (Evans et al., 2011; Fuentes et al., 2014; Klein et al., 2010). The consequence of ignoring interacting threats and future change is that we may under or overestimate the benefits of abating a single threat (Auerbach et al., 2015; Evans et al., 2011; Mantyka-Pringle et al., 2015). Furthermore, the cost of abating more than one threat at a time may not be additive (Crain et al., 2008). Given the varying costs and benefits of different management actions, this has important implications for deciding upon the most appropriate actions to take.

The prioritization of management actions and resources for the conservation of biodiversity within freshwater ecosystems has never been so essential. Due to intensive human use freshwaters are among the most seriously threatened and modified environments on the planet (Vörösmarty et al., 2010). Key disturbances, such as water extraction,

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dams, invasive species, over-harvesting of fish, pollution, and modifications to riparian and in-stream habitats have heavily altered freshwater ecosystems and continue unabated across the globe (Vörösmarty et al., 2010). In addition, there is evidence that climate change interacts with land-use change to affect runoff, river flow regimes, water temperature, evaporation rates, and in turn biodiversity (e.g. Anteau, 2012; Nelson et al., 2009; Peterson and Kwak, 1999; Porter et al., 2013). Yet, conservation planning efforts in freshwater environments have been few compared to terrestrial and marine environments with only a handful of studies prioritizing actions for the conservation of freshwater biodiversity whilst minimizing costs (Januchowski-Hartley et al., 2011; Moilanen et al., 2011; Stewart-Koster et al., 2010; Ticehurst et al., 2007). Further, no freshwater decision framework has accounted for interactions between stressors.

One approach for dealing with interactions between stressors is Bayesian Networks (BNs). BNs are probabilistic models that represent conditional dependencies between nodes in a directed acyclic graph (Kjaerulff and Madsen, 2008). The nodes represent variables that affect some outcome of interest and the links represent interactions between the nodes (Jensen, 1996). Underlying each dependent node is a conditional probability table (CPT) that specifies the probability of each state conditional on other variables (Marcot et al., 2006). BNs are better suited than other techniques/models for situations where considerable uncertainty exists because of the relative ease of combining qualitative (or subjective) and quantitative data (e.g. Ban et al., 2014; Smith et al., 2007). Data feeding into BNs can be based on expert judgment through an expert elicitation process and/or empirical or modeled data about the relationships of interest (Martin et al., 2015). When the BN structure has been fully specified, and the CPTs are parameterized, the model can be used for predictive reasoning about uncertain systems (e.g. Ban et al., 2015; Mantyka-Pringle et al., 2014). For decision-making processes, BNs can also be modified to incorporate the relative costs and benefits of management actions. Such models are known as Bayesian decision networks (BDNs) and are used to model the most appropriate decision given estimated costs and benefits (e.g. Ticehurst et al., 2007). Integration of this information with interactions into decision making is a key gap that needs to be addressed for successful and effective conservation.

To address this important issue we develop an approach for examining how climate change and land-use change determine conservation priorities for conserving freshwater biodiversity under future climate and land-cover change scenarios. We use a BDN to illustrate how to prioritize freshwater conservation and rehabilitation management actions for protecting freshwater macroinvertebrates and fish richness (i.e. stream and riparian restoration, farm/land management, restoration of natural flow, and best practice erosion control) and apply it to rural and urban areas of South East Queensland (SEQ), Australia. While BNs are generally used to depict causal reasoning, they are also often used to represent the correlative structure between variables. The BDN model in this paper contains a mix of both causal and correlative structures. BDNs are particularly useful for dealing with interacting stressors and this is the first use of BDNs for prioritizing freshwater management actions whilst accounting for multiple interacting stressors and future global change.

2. Materials and methods

2.1. South East Queensland study region

SEQ covers an area of nearly 23,000 km^2 with 15 major river catchments and numerous sub-catchments (= watersheds) (Abal et al., 2005). The rivers and streams of SEQ are under increasing pressure from agricultural activities and intensive urbanization, which places pressure on the receiving waters of Moreton Bay — an area of high conservation value (Abal et al., 2005). SEQ is the fastest growing region in Australia, with 754,000 new dwellings expected to be developed by 2031 to accommodate population growth (OUM, 2009). SEQ has only 25% of its native vegetation remaining and predicted increases in the number of dwellings are therefore likely to cause further impacts on native habitat and the ecological health of its waterways. In 2002, the Queensland Government established an Ecosystem Health Monitoring Program (EHMP) in SEQ to assess the effectiveness of management and planning activities aimed at improving SEQ's waterways in the face of global change (Bunn et al., 2010). Up until 2014, the EHMP involved the bi-annual assessment of 135 freshwater sites throughout SEQ, classified by stream order (one to eighth orders), stream type (upland, coastal, lowland) and land-use (e.g. urban, cropping) (see Bunn et al., 2010) (Fig. 1), and reported on five ecological indicators encompassing eighteen separate indices (EHMP, 2012). Data on water quality (including nutrients), aquatic macroinvertebrates and fish from the 135 EHMP sites were used in deriving the BDN presented here so our outputs are directly relevant to real decision-making.

2.2. Management actions

We reviewed local, regional and state management plans and scientific literature to build an understanding of the management actions that could be used as rehabilitation and adaptation strategies for freshwater biodiversity conservation in SEQ under a changing climate. The BDN framework and potential actions, developed during the review phase, were presented to key stakeholders in SEQ for discussion. Stakeholders provided feedback on the management actions to ensure the actions and outputs investigated were realistic and appropriate for local management needs. The decision nodes described in Table 1 represent a summary of the most practical management actions that could be investigated in SEQ.

2.3. Bayesian decision network

We used a validated BN that identified the major causal links between climate (i.e. air temperature, precipitation and rainfall variability) and land-cover (i.e. the amount of hard impervious surfaces and the amount of riparian vegetation) on freshwater biodiversity (i.e. macroinvertebrate taxa richness and native fish species richness) in SEQ as a baseline (Mantyka-Pringle et al., 2014; see Fig. 2 for a conceptual model). The BN included nitrogen, phosphorus, volume of runoff and water temperature as variables in the model, because they are among the most important drivers of freshwater biodiversity loss (linked to land-cover change) identified in the literature (see Appendix A for a review) and represent some of the greatest environmental changes expected to occur in the study region (e.g. increased urban development, vegetation clearing and rising temperatures). A ‘nutrient’ variable was included to represent the effect between higher nitrogen, phosphorus, runoff and rainfall variability caused by climate and land-use change (i.e. nutrient load; as rainfall becomes more variable the nutrient load is greater, see Appendix A). Elevation was also included because it is an important natural determinant of macroinvertebrate and fish distributions in SEQ and elsewhere (see Appendix A for an overview of the conceptual model and the relationships/links between the nodes). Macroinvertebrate taxa richness and fish species richness were chosen as indices based on their statistically strong association with the disturbance gradient in this study region (Bunn et al., 2010) and because they are generally sensitive to multiple stressors (e.g. Statzner and Bêche, 2010; Stendera et al., 2012).

The spatial resolution of the network is the site and the extent is the SEQ region. With 75% of the 135 EHMP sites, the BN was updated to learn from the data while the remaining 25% of the 135 sites were used to test and validate the model. Prior to parameterization, all variables in the BN were categorized into states (classes) using the 33rd and 66th percentile values of each dataset and/or via consultation with freshwater scientists and managers who were familiar with the study region (see Appendix B for more details on these datasets). The BN was modified into a BDN by incorporating available management