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REVIEW

Meeting the challenge of interacting threats in freshwater ecosystems: A call to scientists and managers

Laura S. Craig[*], Julian D. Olden[†], Angela H. Arthington[‡], Sally Entrekin[§], Charles P. Hawkins[‖], John J. Kelly[¶], Theodore A. Kennedy[**], Bryan M. Maitland[††], Emma J. Rosi[‡‡], Allison H. Roy[§§], David L. Strayer[‡‡,‖‖], Jennifer L. Tank[¶¶], Amie O. West[***] and Matthew S. Wooten[†††]

Human activities create threats that have consequences for freshwater ecosystems and, in most watersheds, observed ecological responses are the result of complex interactions among multiple threats and their associated ecological alterations. Here we discuss the value of considering multiple threats in research and management, offer suggestions for filling knowledge gaps, and provide guidance for addressing the urgent management challenges posed by multiple threats in freshwater ecosystems. There is a growing literature assessing responses to multiple alterations, and we build off this background to identify three areas that require greater attention: linking observed alterations to threats, understanding when and where threats overlap, and choosing metrics that best quantify the effects of multiple threats. Advancing science in these areas will help us understand existing ecosystem conditions and predict future risk from multiple threats. Because addressing the complex issues and novel ecosystems that arise from the interaction of multiple threats in freshwater ecosystems represents a significant management challenge, and the risks of management failure include loss of biodiversity, ecological goods, and ecosystem services, we also identify actions that could improve decision-making and management outcomes. These actions include drawing insights from management of individual threats, using threat attributes (e.g., causes and spatio-temporal dynamics) to identify suitable management approaches, testing management strategies that are likely to be successful despite uncertainties about the nature of interactions among threats, avoiding unintended consequences, and maximizing conservation benefits. We also acknowledge the broadly applicable challenges of decision-making within a socio-political and economic framework, and suggest that multidisciplinary teams will be needed to innovate solutions to meet the current and future challenge of interacting threats in freshwater ecosystems.

Keywords: multiple threats; stressors; management; aquatic ecosystems

Introduction

Streams, rivers, and lakes provide fresh water that supports life and services vital to human well-being (Aylward et al., 2005; Vörösmarty et al., 2005; Carpenter et al., 2011). Given the fundamental importance of fresh waters to society, governments around the world have enacted legislation, policies and regulations including the Clean Water Act (United States), the Water Framework Directive (European Union), and the Water Act (Australia) to broadly protect these ecosystems from a variety of human

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[*] Science and Economics Program, American Rivers, Washington, District of Columbia, US

[†] School of Aquatic and Fishery Sciences, University of Washington, Seattle, Washington, US

[‡] Australian Rivers Institute, Griffith University, Nathan, Queensland, AU

[§] Biology Department, University of Central Arkansas, Conway, Arkansas, US

[‖] Department of Watershed Sciences, National Aquatic Monitoring Center, and Ecology Center, Utah State University, Logan, Utah, US

[¶] Department of Biology, Loyola University Chicago, Chicago, Illinois, US

[**] U.S. Geological Survey, Southwest Biological Science Center, Flagstaff, Arizona, US

[††] Program in Ecology and Department of Zoology and Physiology, University of Wyoming, Laramie, Wyoming, US

[‡‡] Cary Institute of Ecosystem Studies, Millbrook, New York, US

[§§] U.S. Geological Survey, Massachusetts Cooperative Fish and Wildlife Research Unit, Department of Environmental Conservation, University of Massachusetts, Amherst, Massachusetts, US

[‖‖] Graham Sustainability Institute, University of Michigan, Ann Arbor, Michigan, US

[¶¶] Department of Biological Sciences, University of Notre Dame, Notre Dame, Indiana, US

[***] Blue Ethos, Tallahassee, Florida, US

[†††] Sanitation District No. 1 of Northern Kentucky, Fort Wright, Kentucky, US

Corresponding author: Laura S. Craig (lcraig@americanrivers.org)

activities. Although such protections have improved resource conditions, freshwater ecosystems continue to face impacts from numerous ongoing and emerging threats (See **Figure 1** for definition of terms).

Scientists and natural resource managers generally have a solid understanding of individual threats, including urban and agricultural land use, resource extraction, water withdrawals, habitat alteration and fragmentation, emerging contaminants, and non-native species (Malmqvist and Rundle, 2002; Dudgeon et al., 2006; **Figure 2**), as well as their associated abiotic alterations and biotic effects (**Figure 3**). Yet, the numerous and varied interactions among threats are still somewhat poorly understood. Furthermore, climate change is likely to be superimposed on other threats, increasing the challenges for conservation and restoration (Dudgeon et al., 2006; Ormerod et al., 2010). Multiple threats and alterations can lead to combined effects being greater (synergism), less than (antagonism) or equal to the sum (additive) of their individual effects, or can even manifest in the opposite direction to the independent effects (reversals) leading to striking ecological surprises. A recent synthesis indicated that the net effects of paired alterations in freshwater ecosystems were more frequently antagonistic (41%) than synergistic (28%), additive (16%), or reversed (15%; Jackson et al., 2016). Other reviews support this finding in a range of ecosystems (Côté et al. 2016; Nõges et al. 2016). The majority of the published literature has focused on multiple local alterations, whereas the examination of multiple threats – the focus of this paper – is much more limited.

Multiple threats and their interactions pose significant and specific challenges to natural resource management (**Figure 4**). For paired threats that generate additive or synergistic effects, management focusing on a single threat should render a positive outcome (Brown et al., 2013). For example, managing for hydrologic alteration resulting from dam operations by delivering an environmental flow regime may constrain the establishment of harmful non-native species (Bunn and Arthington, 2002). However, in ecosystems affected antagonistically by paired threats, both may need to be removed or moderated to produce any substantial ecological recovery due to positive co-tolerance (Vinebrooke et al., 2004; Brown et al., 2013; Piggott et al., 2015). Managing for the net ecosystem effects of three or more threats and their related alterations is even more complex, as the number of connecting relationships increases exponentially with the number of threats and the contribution of individual threats to the observed outcome may be less apparent. For these reasons, we must continue to further understanding of how threats interrelate, explore the ecological mechanisms underlying complex relationships, and strive to produce actionable science that leads to improved outcomes when faced with managing multiple threats.

Considering multiple, interacting threats can be overwhelming, or even paralyzing, for both scientists and managers, slowing progress towards developing knowledge and solutions in both arenas. Scientists are challenged to develop metrics that are suitable for quantifying the impacts of multiple threats, design experiments that reveal interactions between threats, discover mechanisms of action, and disentangle effects (Segner et al., 2014; Nõges et al., 2016). Practitioners are confronted by the reality that existing tools – including restoration, upland practices, protection, and policy – may be incapable of addressing a full suite of threats and effects. As a result, only a subset of threats may be manageable, and the scope for improvements in ecological condition may be narrow.

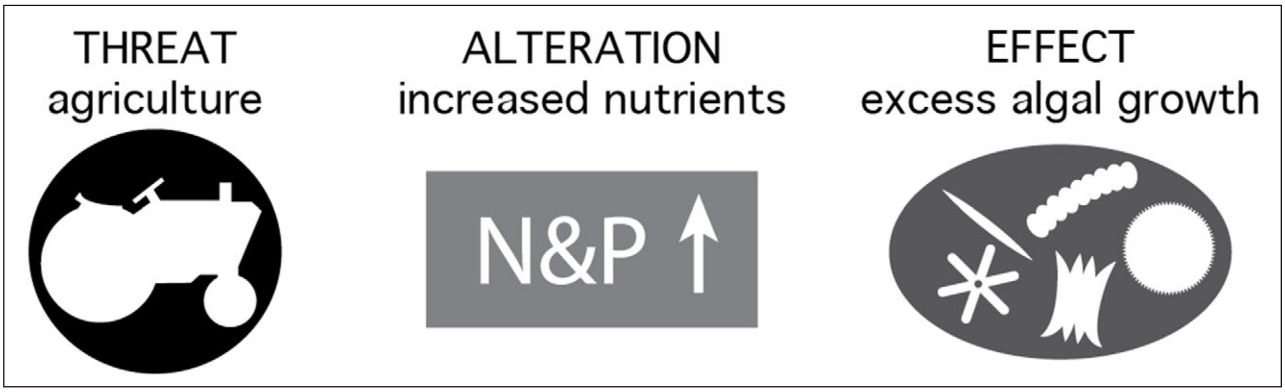

Figure 1: Definition of terms illustrated using agriculture as an example threat. The terms threats, drivers, stressors, and pressures have all been used, often interchangeably, to refer to human activities that affect aquatic ecosystems (Richter et al., 1997; Kristensen, 2004; Vörösmarty et al., 2010; Norton et al., 2015). Here, we use 'threat' to refer to human-caused drivers of environmental change, and the terms 'alteration' and 'effect' to refer to the environmental changes they produce and the ecological responses to those changes, respectively. Use of the neutral terms alteration (versus stressor or pressure) and effect (versus impact) reflects our appreciation that not all outcomes are negative. We prefer to use the negatively-biased term threat over more neutral terminology (e.g., driver) because it better reflects the context of our discussion: the management of adverse effects to freshwater ecosystems. Regardless of whether the drivers, alterations, and effects are positive or negative, the ideas presented in this paper may be applied in a general way. DOI: https://doi.org/10.1525/elementa.256.f1

Figure 2: In most watersheds, ecological responses are the result of complex interactions among multiple threats. Photos illustrate a variety of threats including those associated with urban **(A, B, C)** and agricultural **(D, E)** land use, resource extraction **(F)**, hydrologic alteration **(G)**, non-native species **(H, I)**, habitat fragmentation and alteration **(J, K)**, and climate change **(L)**. Photo credits: S. Brown/National Geographic [B], U.S. Geological Survey [C], U.S. Department of Agriculture [E], Lancaster Online [G], National Park Service [H], A. Rehana [I], U.S. Fish and Wildlife Service [J], L. Craig/American Rivers [K], and National Weather Service [L]. DOI: https://doi.org/10.1525/elementa.256.f2

Continuing to study and manage threats in isolation (**Figure 3**), whilst useful in rare circumstances, fails to serve the future health of freshwater ecosystems, particularly as the risks of management failure are great (i.e., loss of biological and functional diversity, goods, services, and ecosystem values). Our objectives include highlighting the urgent need for improved understanding and management of multiple, interacting threats; identifying opportunities to enhance the science and fill significant knowledge gaps; and providing guidance for addressing mounting, management challenges. This paper is intended for both scientists and natural resource managers as sharing the perspectives of both communities in a single resource benefits our ability to meet the challenge of interacting threats in freshwater ecosystems (**Table 1**).

Why should we consider multiple threats?

It is well recognized that an improved understanding of multiple threats can improve our ability to address management challenges (Allan et al. 2013; Kuehne et al., 2017). Simultaneous consideration of multiple threats will allow us to identify similarities across threats, improve our knowledge of the relationships between threats and the ecological mechanisms underlying those relationships, and reveal patterns of threat co-occurrence that can be used to focus future studies, all of which are relevant to management.

Understanding alteration profiles may allow extrapolation from one threat to another

Threats exert their effects on ecosystems through the specific set of alterations that they impose. Although each threat produces a unique set of alterations, there is

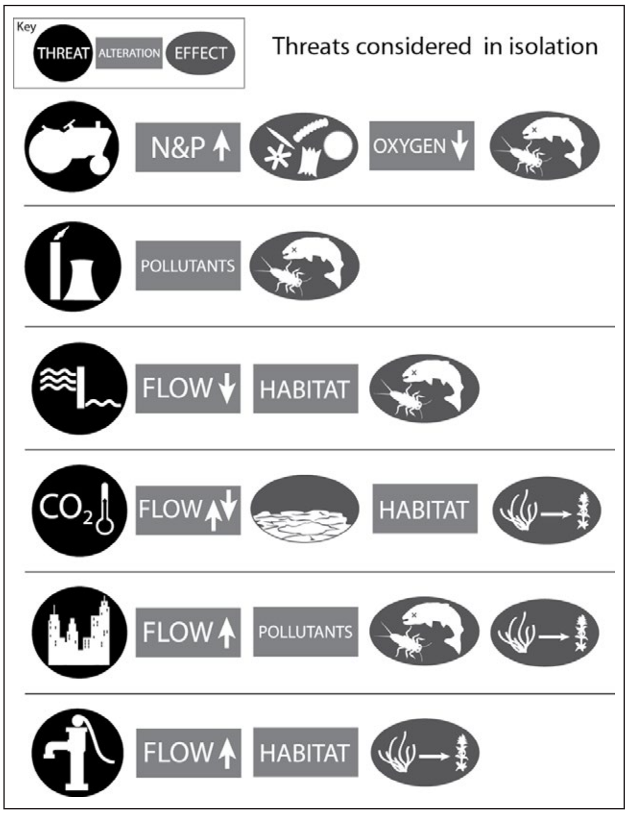

Figure 3: Threats considered in isolation. In isolation, scientists and managers have a generally strong understanding of environmental threats. Most research and management approaches consider single threats (e.g., agriculture, resource extraction, dams, climate change, urbanization, and water withdrawals), the associated abiotic alterations (e.g., increased nutrients, decreased oxygen, increased pollutants, altered flows, altered habitat), and biotic and ecosystem function effects. DOI: https://doi.org/10.1525/elementa.256.f3

considerable overlap in alterations across threats. To the extent that different threats have similar alteration profiles (e.g., two or more shared alterations), our understanding and management of one threat may be cautiously applied to another. For example, both agriculture and urbanization increase surface runoff and introduce pollutants (i.e., pesticides or metals) into freshwater environments. Knowledge about how ecosystems respond and adapt to flow alteration and contaminants derived from studies of rivers in agricultural landscapes may be applied, at least as hypotheses, to the understanding and management of comparable effects in urban streams. For example, the flow regimes of rivers are frequently altered by dams and water release patterns that provide water to irrigated cropping systems, and numerous ecohydrological relationships quantify the ecological effects (e.g., Poff and Zimmerman, 2010). Urban streams experience altered flow patterns of similar nature, particularly higher discharge during normally low flow seasons due to enhanced runoff from hardened surfaces and reduced evapotranspiration. There is growing awareness of the scope for transferability of ecohydrological relationships across river systems and climatic regions (Poff et al., 2010).

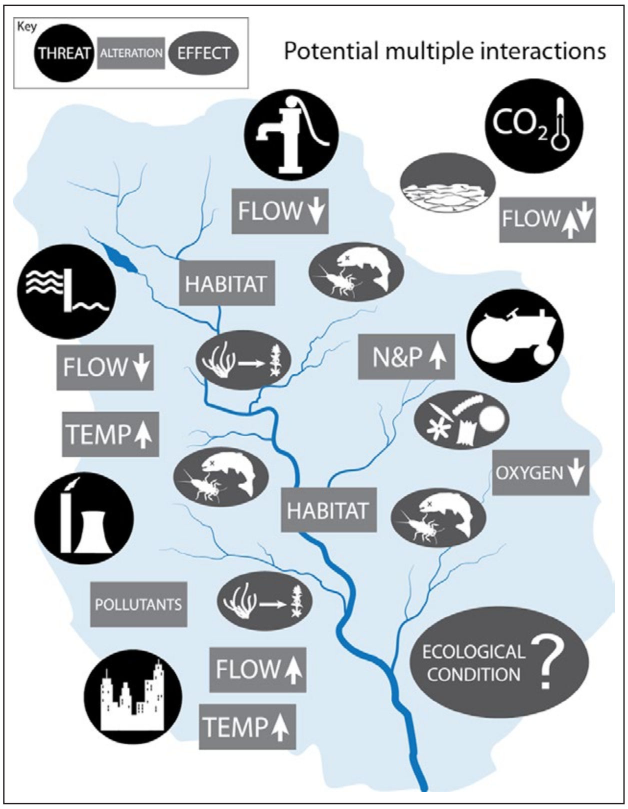

Figure 4: Multiple, interacting threats in a watershed creates challenges for natural resource management. Most watersheds experience multiple threats. Depending on the location, types, and intensity of interacting threats throughout the watershed, stream alterations are expected to vary along the network and through time, resulting in different biotic and ecosystem effects. Here, we depict only a few threats, alterations, and effects, with the overarching impact of climate change. There is limited understanding of the cumulative effects to ecosystem condition in the presence of multiple, interacting threats. It is critical to consider the spatial and temporal consequences of multiple threats and stressors throughout watersheds to advance improve management of multi-threat watersheds. DOI: https://doi.org/10.1525/elementa.256.f4

Threats may moderate the adverse effects of other threats

If threats have antagonistic alteration profiles, they may cancel out one another, at least in part. For example, beds of the non-native plant *Trapa natans* (water-chestnut) in the Hudson River (NY, USA) denitrify large amounts of nitrate (Tall et al., 2011) reducing the deleterious effects of nutrient loading from agriculture, industry, and urbanization in the surrounding watersheds. Recognizing this role of *T. natans* can help to improve management of both nutrients and non-native species in the region. This is not to suggest that non-native species should be introduced into new ecosystems, but rather to encourage recognition that, if already present, these species may provide useful ecological functions that moderate the effects of other threats; and that these functions should

Table 1: Challenges posed by multiple, interacting threats in freshwater ecosystems; all of which are described in greater detail in the text. DOI: https://doi.org/10.1525/elementa.256.t1

Scientific challenges	Management challenges
1. Examining interactions among 3+ alterations from multiple threats.	1. Identifying all existing or potential threats and alterations in a management area
2. Scaling interactions to watersheds.	2. Selecting restoration, protection, and policy tools suitable for addressing specific groups of threats.
3. Linking alterations to parent threats.	3. Drawing insights from the management of single threats (i.e., prior experience or case studies).
4. Determining the magnitude of the contribution of each threat to resulting alterations and effects.	4. Setting measurable and realistic management goals.
5. Understanding spatial overlap of threats within watersheds and hierarchical connections within stream networks.	5. Monitoring ecosystem response to assess progress towards meeting management goals.
6. Characterizing trajectories of threats and temporal scales of impact and recovery.	6. Establishing a framework for communication among scientists, managers, and the public to encourage transfer of knowledge.
7. Assessing cumulative effects of multiple threats.	7. Identifying the origin of each threat (i.e., responsible agents).
8. Selecting response metrics to best quantify and integrate threats and alterations.	8. Understanding the spatio-temporal dynamics of each threat in an unmanaged system.
9. Incorporating ecosystem function metrics to understand cumulative responses to alterations.	9. Identifying and implementing those management strategies that are likely to be successful despite uncertainty about interactions among threats.
10. Linking species responses and ecosystem functions in multiple threat scenarios.	10. Avoiding unintended consequences of management actions
11. Predicting outcomes of multiple threats and alterations.	11. Maximizing conservation benefits of management actions
12. Assessing future risk from multiple threats.	12. Engaging in collaborative decision-making with scientists, policy makers, and the public.

be considered prior to management (e.g., via removal or control; Schlaepfer et al., 2011). Antagonistic alteration profiles between other combinations of threats may likewise be relevant to their best joint management.

Threat co-occurrence may inform science and management

Most freshwater ecosystems are exposed to multiple threats (e.g., Tockner et al., 2010; Vörösmarty et al., 2010; Strayer et al., 2014) and these threats are not randomly distributed in space and time. For example, many rivers in and around urban areas are subject to inputs of contaminants and nutrients (e.g., Kaushal et al., 2014; Lee et al., 2016), direct modification and/or presence of infrastructure such as hardened shores, dams, and road crossings (e.g., Strayer and Findlay, 2010), altered hydrology (Walsh et al., 2005), multiple invasions of non-native species (e.g., Liendo et al., 2016), and climate change. As a result, scientists and managers working in different urban settings will consider the single and combined effects of a common set of threats and alterations; freshwater ecosystems in other settings will have different threat profiles. Threat co-occurrence suggests that it might be useful to determine how frequently different threats coincide, if at all, at both global and regional scales (e.g., as in Vörösmarty et al., 2010), and then focus research on those combinations of threats that occur most frequently, rather than studying all possible combinations of threats.

Enhancing the science of multiple, interacting alterations

Mounting evidence over the last two decades (**Figure 5**) suggests that the net effects of multiple interacting alterations in freshwater ecosystems can differ from the effects of individual alterations (Jackson et al., 2016; Nõges et al., 2016). The majority of research has focused on specific alterations (e.g., altered hydrology, temperature, contaminants) rather than the sources of these alterations (i.e., threats). Predominantly, these studies focus on two or three alterations (Jackson et al., 2016; Nõges et al., 2016). Moreover, studies have typically deployed mesocosm experiments with species biomass or abundance as the response variable, limiting our ability to scale up to the reach, ecosystem, or even watershed scale, or extrapolate to other types of alterations (**Figure 6**). Because most watersheds are exposed to several threats that exert varying types and levels of alteration on ecosystems at various spatial and temporal scales, new and actionable science is required to better inform management actions. Below, we explore three core areas where scientific advancement is critical.

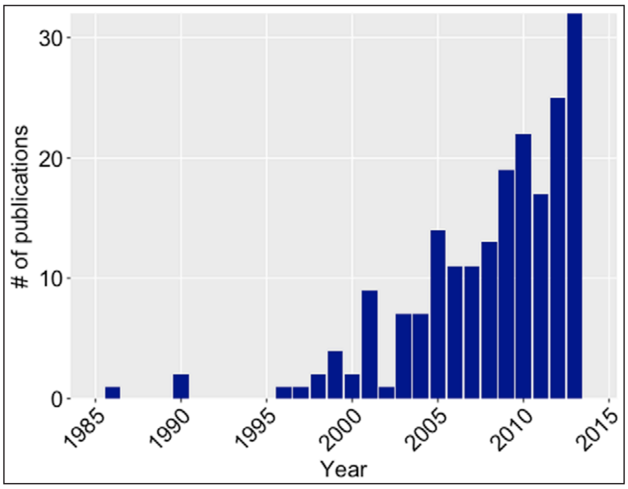

Figure 5: Number of peer-reviewed multiple stressor studies (1986 to 2013); data from Nõges et al. 2016. DOI: https://doi.org/10.1525/elementa.256.f5

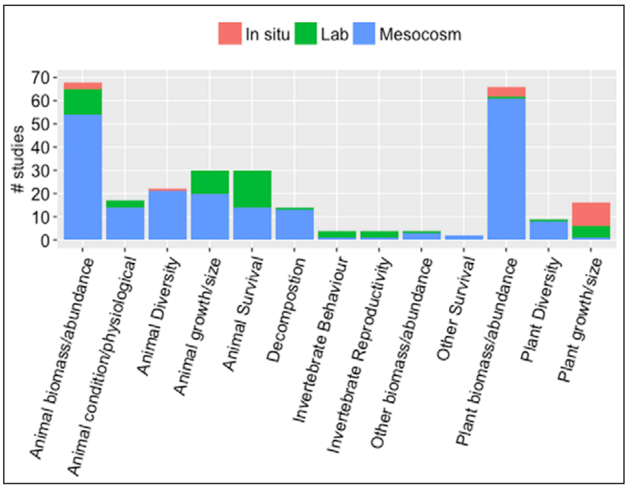

Figure 6: Number of in situ, laboratory, and mesocosm studies of multiple stressors for different response metrics; data from Jackson et al. 2016. DOI: https://doi.org/10.1525/elementa.256.f6

Linking ecological alterations to threats

Scientists continue to be challenged in linking ecosystem alterations (e.g., salinization or eutrophication) with their parent threat(s), when multiple threats could contribute to the same alteration within a single watershed. For example, dam operations, urbanization, and climate change can all alter hydrology (Poff et al., 2006; Poff and Zimmerman, 2010), although they may have distinct spatial and temporal fingerprints. Likewise, agriculture, urbanization, and hydraulic fracturing can all cause salinization (Cañedo-Argüelles et al., 2016) and eutrophication (Carpenter et al., 1998; Entrekin et al., 2011). Where threats co-occur, the magnitude of the contribution of each threat to producing the observed environmental alterations and resulting ecological effects is often unclear. For example, within a mixed land use watershed, it is often difficult to apportion the sources of nutrient impairment and, subsequently, decide where to focus management actions. Yet linking threats to alterations is critical for ensuring effective management by addressing primary causes. Meta-analyses using multiple lines of evidence are often the only tools available to identify threat-alteration linkages, but may be less than ideal due to data gaps and inconsistent use of terms (Webb et al., 2017). Alteration-effect relationships have been informed mostly by controlled, manipulative experiments, often conducted in mesocosms, and do not have the ability to scale to the field in a way that directly quantifies the contributions of threats to alterations and subsequent responses (Jackson et al., 2016; **Figure 6**).

Novel conceptual frameworks that integrate complex interactions among alterations have been useful in formulating testable hypotheses for laboratory and field-based experiments (Vander Laan et al., 2013), while geospatial models exist that predict threat-alteration extent and intensity (Paukert et al., 2011). Yet it is rare to find field-based linkages between several alterations and measured ecological effects required for regulatory action. Developing threat-specific "fingerprints" is one solution to identify alterations associated with observed threats. For example, the presence of signature isotopes and/or conserved elements can link contaminated water with hydraulic fracturing (Osborn et al., 2011). Additionally, new developments in molecular fingerprinting for *E. coli* now distinguish cell surface properties that can partition multiple threats, making *E. coli* an indicator organism for dissolved vs. particulate transport of contaminants (Liang et al., 2016). When quantitative analysis of alterations is not practical, expert elicitation can be used to rapidly rank and prioritize alterations with testable links to threats (sensu Smith et al., 2015). Continental-scale monitoring of selected potential alterations from identified threats can also be achieved from long-term studies and coordinated sampling efforts like those from ongoing programs in Europe (e.g., European Managing Aquatic ecosystems and water Resources under multiple Stress (MARS)) and North America (e.g., Long-Term Ecological Research (LTER)) that are identifying ecological effects of multiple alterations (Hering et al., 2015). Despite these existing efforts, there remain numerous research gaps on continental and global scales.

Understanding the spatial and temporal extent of interactions

The sources and effects of threats are varied in both space and time. Some threats operate at global (e.g., climate) and regional (e.g., land cover) scales, whereas others manifest from single point sources (e.g., chemical contaminant inputs, water withdrawals, dams, hydropower operations, waste disposal) with effects transmitted downstream, upstream, and laterally in rivers (Pringle, 1997; Bunn and Arthington, 2002). Over time, threats can expand or contract, intensify or dissipate, in response to human activities that degrade or attempt to restore ecosystems (Davis et al., 2015). Nonlinear responses to threats, whereby ecosystems change dramatically from one state to another at a given alteration level, ultimately lead to different temporal scales of impact and recovery (Dodds et al., 2010). Multiple alterations can also act simultaneously or sequentially (Taniwaki et al., 2016), including one alteration triggering another, further challenging the ability to identify and isolate the role of individual threats in the landscape. A better understanding of when and where threats overlap can help determine the relevance of interactions to guide scientific studies and inform management.

Diverse research approaches are needed to better understand the cumulative effects of multiple threats operating at different spatio-temporal scales and how alterations are manifested hierarchically across the stream network. Multi-factorial laboratory studies, along with spatially nested or replicated field experiments, can be used to understand if and where interactions among alterations are ecologically relevant (Pigott et al., 2015). These experimental efforts have most often only examined pairs of alterations (rather than suites of alterations), with the goal of disentangling the effects of individual factors (Nõges et al., 2016). The use of replicated, artificial streams has proven powerful for revealing complex interactions that might be confounded at larger spatial scales (e.g., Kuehne et al., 2012); however, most experiments are executed at small spatial scales and are typically of short duration. Similarly, field-based research has been critical in revealing how interactions among alterations vary in response to temporal changes in threats (e.g., intensification; Davis et al., 2015) or as a result of inherent ecosystem feedbacks (Dodds et al., 2010), but often lacks the controls necessary to identify mechanisms of effect.

Combining and coordinating lab and field-based studies could help to better elucidate complex interactions at multiple scales. Given that basin scale experiments will continue to be challenging, novel statistical and modelling tools will be critical for scaling up and predicting responses to multiple alterations over large spatial and temporal scales. Large water quality and biomonitoring datasets containing information from multiple locations at different times, coupled with geospatial analyses, offer opportunities to quantify the net effects of multiple alterations in natural settings (Feld et al., 2016; Van Metre et al., 2016; Johnson et al. 2017). Such time series approaches are, however, limited by available data, which cover noticeably shorter time periods in flowing waters compared to lakes (Nõges et al., 2016). Continued efforts focusing on the spatio-temporal aspects of combinations of threats can help guide when and where to focus future management and restoration.

Determining how to measure the effects of multiple threats

Meeting the challenge of predicting the impacts of multiple threats requires greater attention to the attributes of response metrics, rather than a sole focus on the description of alterations (Segner et al., 2014). Nevertheless, logistic constraints may impinge on threat impact assessments (e.g., limited time, money, and personnel), and there remains an ongoing challenge of choosing metrics that best quantify the effects of multiple threats and their associated alterations. Jackson et al. (2016) found that responses in diversity metrics were most often additive, whereas functional metrics demonstrated more varied responses. For example, eutrophication and a warmer climate act synergistically in shallow lakes, and are associated with increased rates of primary production as a result of cyanobacterial blooms, while algal biodiversity may be significantly restricted by cyanobacterial dominance (Kosten et al., 2012). It is clear that the choice of response metric contributes to variation in the net effects of combinations of alterations given the likelihood for "response diversity" to environmental change (Elmqvist et al., 2003).

Water resource managers have generally used spatially explicit response metrics to target locations with the highest cumulative alteration, frequently focusing on indices of biotic integrity or community composition (i.e., macroinvertebrates, fishes). Yet metrics of ecosystem function (e.g., metabolism, nutrient uptake and transformation, decomposition, secondary production) may be more useful for characterizing cumulative system response to a wide range of environmental alterations, and are especially effective when used in combination with organismal response (Rosi-Marshall and Royer, 2012; Taniwaki et al., 2016), as structural and functional responses may differ (or show stronger responses in combination) and link to different management objectives.

Understanding the relationship between species-level responses and ecosystem function needs further study (McKie and Malmqvist, 2009), particularly given the limited understanding of interacting threats and associated alterations. Clearly, it is not feasible or efficient to measure all variables all the time, and the choice of response metrics must consider research and management objectives. Given limited resources, trait-based metrics (i.e., metrics based on species characteristics rather than species identities) are useful in bridging structural and functional characteristics, and can assist in identifying how ecosystem function is changing without directly measuring functions (e.g., Moore and Olden, 2017). Another approach is to focus on metrics that integrate threats. For example, hydrologic metrics are integrative measures that can be used to define environmental flow regimes that will support freshwater ecosystems and maximize freshwater diversity in the face of combined land use intensification, water withdrawals, and climate change (Davis et al., 2015). Concurrent analyses of alteration interactions using both structural and ecosystem response metrics will be critical for optimizing management and restoration efforts in the future (Poff et al., 2010; Allan et al., 2013).

Advancing the prediction of future risk from multiple threats

Our suggested research targets – threat-alteration linkages, spatial and temporal extent, and response metrics – can be used to understand existing ecosystem conditions and the causes of impairment, but also to predict future risk and outcomes of multiple threats and interacting alterations on freshwater ecosystems. Long-term, coordinated research is needed to develop predictive models where the ecological effects from multiple threats can be forecast by scaling from individuals to responses in ecosystem function. Trait-based approaches may allow for scaling from individuals to functions by obtaining a first approximation of response diversity across landscapes (Moore and Olden, 2017). In Europe, considerable resources have been dedicated to investigate the effects of multiple alterations on freshwater and estuarine ecosystems to inform the European Union's Water Framework Directive. Research from the MARS Project includes multiple approaches (i.e., experimental, case studies, large-scale data analysis) that may also be useful to inform research on multiple threats in freshwater ecosystems.

Improving the management of multiple threats

The challenges faced by freshwater managers are increasing in complexity and urgency (Hart and Calhoun, 2010) and the risks of management failure are great, including loss of biodiversity, ecosystem goods and services, and continued decline of ecological integrity (Kuehne et al., 2017). While science and management communities recognize that most freshwater ecosystems are impacted by interacting threats, management may be poorly equipped to address the complex issues and novel ecosystems that arise from these interactions. For example, conservation actions often focus on addressing individual alterations without a satisfactory understanding of whether interactions with other alterations exist. If interactions with other alterations are either absent, synergistic, or additive, the management of single alterations should yield positive results (Brown et al., 2013); for example, if two threats contribute to increased nitrogen pollution, management of one of these threats should reduce nutrient loads. But antagonistic interactions are more prevalent than other types, and management of individual alterations without a true understanding of multi-threat interactions may be ineffective or detrimental (Brown et al., 2013; Jackson et al., 2016). When the nature of multi-threat interactions is unknown or uncertain, managers may be wary of selecting and implementing conservation actions because of the potential for negative ecological consequences, and risk of wasted effort and expense (Hart and Calhoun, 2010; Côté et al., 2016). Moreover, practitioners are confronted by the reality that existing restoration, protection, and policy tools may be incapable of addressing interacting alterations, that only a subset of threats and alterations may be manageable, or that resulting improvements in ecological function may be limited. Below we present guidance for confronting the significant management challenges associated with multiple threats, recognizing that an ideal approach will depend upon the specific threats and alterations that are present, their interactions, context, and other variables.

Consider transferability of lessons learned from managing individual threats

Whereas managing for multiple freshwater threats is relatively new and case studies are few, management and mitigation of individual threats is more mature with numerous case studies from which to draw insights. Some of the 'lessons learned' from the management of single threats include the importance of setting measurable goals (Christensen et al., 1996), monitoring ecosystem response to management actions (Bernhardt et al., 2005), and establishing a framework for communication among scientists, managers, and the public. Setting measurable goals is critical to any management endeavor, and the challenge of managing for multiple threats makes setting measurable goals all the more important. For example, restoration of a stream or river to pre-impact conditions is likely unrealistic in the context of multiple threats or alterations, but improvement from a degraded baseline is often conceivable. Scientists, managers, and the public all play unique and important roles in setting goals, and thus communication among these groups is essential. Monitoring ecosystem response using appropriate response metrics is critical for assessing progress towards achieving stated goals, and because there are few examples of management actions designed to address multiple threats, evaluating these approaches is especially important. Efforts aimed at measuring the success of management and restoration in ecosystems experiencing multiple threats and alterations will necessarily need to be expanded to exceed rates of monitoring reported in the literature (e.g., Bernhardt et al., 2005; Roni et al., 2008). It is critical to share results and lessons learned across projects, and new interactive platforms for sharing results among managers may be needed. With effective transfer of knowledge, new insights about the interactive effects of multiple threats and alterations from monitoring and research can support gradual improvements to the success of freshwater management approaches.

Consider how the characteristics of individual threats may inform multi-threat management

Several threat attributes might be relevant in determining appropriate freshwater management strategies, including responsible agents (i.e., individuals, communities), intent (i.e., deliberate or unintentional), mode of causation (i.e., direct or indirect), breadth of threat targets (i.e., narrow and focused on a few parts of the ecosystem or broad and affecting many parts of the ecosystem), spatio-temporal dynamics (i.e., intensity and spatial extent), and, in rivers, directionality of effects (i.e., upstream, downstream, and/or lateral). We hypothesize that knowing the agents responsible for the presence of the threat (i.e., the origin of the threat) and its spatio-temporal dynamics in an unmanaged system will be helpful for identifying which approaches (e.g. outreach/education, incentives, regulation, iterative or adaptive management) are likely to be the most effective for a grouping of threats.

Responsible agents – Two attributes of the agents accountable for threats to freshwater ecosystems may have important implications for management: their relationship to the affected ecosystem (i.e., involved, peripheral, removed) and the nature of their constituency (e.g., individuals, institutions, society). The extent to which responsible agents are involved with the affected ecosystem, either by geographic proximity, economic linkages, or other mechanisms, seems likely to determine the likelihood that the condition of the ecosystem directly affects the agent, and, therefore, the effectiveness of different management strategies. For example, we hypothesize that a community that experiences local flooding resulting from urban runoff may be more motivated to address a threat that they contributed to, and which also affects them, than a community whose urban landscape contributes to flooding in a distant downstream community.

The most suitable management approaches may also depend on whether the responsible agent is an individual, a clearly defined group or institution (e.g., a community, company, governmental agency), or a large, diffuse group (e.g., society). Threat management can be particularly difficult when agents are individuals; it can be challenging both to know which individuals need to be targeted and to effectively reach all individual agents. In addition, individuals express a wide range of interests, goals, expertise, and accountability, which probably will hinder any single management approach. When the behavior of many individuals must change to eliminate a serious threat (e.g., preventing species invasions), it may be worth considering whether to remove the decision-making power of individuals through government regulation. Conversely, if ecosystem response to management is proportional to the number of people motivated to act (e.g., voluntary installation of agricultural best management practices to reduce nutrient loading) then management strategies aimed at creating communities of stewards may be preferred. Institutions are less numerous and probably less variable than individuals, and so are more easily identified as responsible agents. For these reasons, it may be practical to craft management approaches tailored to each institution that are informed by its goals (i.e., public good vs. private gain), size, stability, accountability, and ability to change its actions. Finally, threats and alterations that arise from diffuse groups and cross multiple jurisdictions (e.g., climate change) may be best managed with a combination of legislation, regulations, incentives, and customized tools, and is likely to be difficult. In the case of multiple threats, determining the characteristics of responsible agents could allow managers to decide whether the combination of threats is best addressed with universal or targeted strategies.

Spatial and temporal dynamics – When a threat is ongoing and unmanaged, its intensity or spatial extent may be constant or increase (a decrease in intensity or spatial extent of an unmanaged threat seems unlikely to occur in nature). For example, a dam may alter river hydrology and hydraulics, but those effects typically do not deteriorate or spread over time; once the dam is in place, the spatial extent of reaches affected by the impoundment or altered flows, may not change greatly. By contrast, concentrations of persistent, organic pollutants (e.g., PCBs) typically increase over time (Wania and McKay 1996) and the effects of non-native species can increase over time in both intensity and spatial extent (Jeschke et al. 2014). When a threat ceases, the intensity and spatial extent of the related alterations may remain the same (e.g., as with concentrations of insoluble and persistent pollutants), diminish (e.g., as with concentrations of soluble or labile pollutants such as nitrate), or increase (e.g., as with populations of non-native species), with rates of change varying across threats and alterations. The most well-suited management approaches probably will depend, in part, on these spatio-temporal dynamics. For example, for alterations that diminish rapidly in intensity when the related threat is lessened (e.g., labile pollutants), it may be appropriate to establish a management regime that reduces the magnitude of the alteration, monitor for harmful effects, and iteratively manage the threat until observed effects are acceptable. Alternatively, for alterations and effects that will be likely to intensify even after the threat ceases (e.g., as with species invasions), preventative approaches are more likely to be optimal. In the case of multiple threats, an understanding of individual threat dynamics in the absence of intervention could allow managers to develop strategies targeting appropriate spatial and temporal scales, accounting for spatial and temporal autocorrelation in the data, and determining whether threats should be addressed sequentially or concurrently.

Identify and test preferred strategies for managing multiple threats

It is critical to identify and implement management strategies that are likely to be successful or, at a minimum, harmless in spite of uncertainties about the nature of interactions among alterations (Côté et al. 2016). In fact, uncertainty surrounding ecosystem response to multiple threats highlights the urgent need for action by managers and policy makers. Adaptive management is one approach that allows for a reduction in uncertainty by explicitly incorporating learning into the management process (Walters, 1986; Allen et al., 2011). It is a structured approach where resource management actions are designed as experiments with the clear intention of increasing knowledge and decreasing uncertainty. This new knowledge is then iteratively applied to revise management actions and improve ecological outcomes over time (Walters, 1986; Allen et al., 2011). Adaptive management is suitable for addressing multiple interacting threats when a sufficient pool of feasible and controllable management options exists, there is limited risk of causing irreversible harm (e.g., by facilitating species invasions), there are suitable data available on a continuing basis, and scientists, managers, and stakeholders are able to work collaboratively (Allen et al., 2011). It is not suitable for managing all threats and alterations.

For adaptive management approaches to be most effective, we suggest that managers use a hierarchical framework for prioritizing management goals and objectives in systems facing multiple threats. Begin by identifying and managing one threat or alteration that is assumed to have the greatest impact on a particular species or habitat, or is most easily managed. Then, through ongoing and iterative management experiments, practitioners can increase knowledge of the targeted threat's effects, as well as potential interactions with other threats. Such a hierarchical framework, especially when coupled with an ecosystem-based management paradigm (i.e. reach, stream, watershed), would allow managers to identify variation in impacts at multiple scales and account for potential differential outcomes of management decisions (Linke et al., 2011).

Unfortunately, the ability to achieve effective management of multiple threats and alterations may be stymied by high costs of remediation efforts, low commitment to monitoring (particularly where long-term monitoring is needed), and other resource and personnel limitations (Bernhardt et al. 2005). Accordingly, formal methods to systematically prioritize management actions and measure their success are needed. Use of prioritization techniques is a preferred strategy in restoration (Roni et al., 2002), and now comprises families of methods, tools, databases, and practitioners that aim to address multiple alterations simultaneously. In particular, mathematical optimization modeling has shown great promise in guiding ecologically meaningful management decisions given limited budgets (Neeson et al., 2016). Unfortunately, widespread use and implementation of optimization methods has been hindered by limited data availability, high costs of required software and expertise, high computational burden, and lack of transparency to decision-makers (Beechie et al., 2008). But this is rapidly changing as user-friendly spatial decision support tools (e.g., GIS toolboxes) that significantly reduce the technical expertise needed to perform relatively complex optimization analyses are made available (e.g., Neeson et al., 2016; Maitland et al., 2016; McKay et al., 2016).

Avoid unintended consequences and maximize conservation benefits

Natural resource managers are challenged to manage for one problem without impeding their ability to solve another problem, or inadvertently damaging ecosystem goods, services, and values, particularly when alterations interact antagonistically. For example, conservation biologists may face the trade-off that restoring connectivity in a fragmented river system to benefit imperiled fish populations may also lead to invasion by non-native species or the spread of disease from other parts of a watershed (Fausch et al., 2009). These types of unintended consequences can sometimes be avoided if management decisions are grounded in an understanding of historical data and management decisions, threat characteristics, and links between alterations and ecosystem functions, ultimately using this information to weigh the potential benefits and risks of pursuing different management options (McLaughlin et al., 2013; May and Spears, 2012).

Alternatively, managers may be presented with opportunities to achieve multiple benefits when addressing individual threats or alterations. A strategy that identifies and capitalizes on such opportunities can eliminate redundant conservation actions, particularly when the best available science is used to identify interactive associations between alterations (Smith et al., 2015; Jackson et al., 2016). Ancillary benefits to targeted management actions ("conservation co-benefits") include the generation of other desirable ecosystem services, lessening of the negative effects of interconnected alterations, and facilitation of conditions that allow managers to more readily address other threats or alterations. Examples of co-benefits resulting from aquatic resource management include improving water quality and recreational opportunities through implementation of a municipal planning ordinance designed to alleviate flooding. Incorporating co-benefits into management not only increases the cost-effectiveness of conservation (Chan et al., 2011), but may also stimulate the interest of funders and other investors.

Embrace multidisciplinarity and avoid working in silos

A multidisciplinary approach is vital to successfully address multiple threats. Holistic watershed management strategies that integrate expertise across disciplines should provide better protection to streams, rivers, and lakes (Scott, 2015), and have been endorsed by regulatory agencies such as the US Environmental Protection Agency (USEPA, 2008). Yet the increasing diversity of expertise and divergence of work cultures among partners (e.g., scientific researchers, managers, regulatory agencies) makes implementing such strategies difficult (Barquín et al., 2015). The propensity to focus on a single area of expertise can lead individuals or collectives of experts to work in "silos" where disciplines operate independently of one another. This tendency to work in silos is intensified by poor communication including delayed communication of research findings and the absence of a shared language for reciprocal transfer of information, a lack of commitment to developing relationships, and the independent operation of management and regulatory agencies (Bernhardt and Palmer, 2011; Prosser et al., 2015). Outcomes of working in silos include failure to identify applicable research questions or apply the most current science to management, duplication of effort, missed opportunities to achieve conservation co-benefits and avoid unintended consequences, and impeded ability to innovate solutions to the complex problems associated with the simultaneous management of multiple threats. Alternatively, an integrated effort can improve collaboration between scientists with areas of expertise that are linked by management and coordination across agencies with different management responsibilities; for example, bringing together researchers with expertise related to linked nitrogen and phosphorous cycles and food webs when managing water quality and fisheries (see Hartig et al., 1991 for an example from the Laurentian Great Lakes).

Engage in collaborative decision-making

Despite the unique challenges of managing multiple threats in freshwater ecosystems, all management decisions occur within a context of political, social, and economic elements. Collaborative engagement among natural resource managers, scientists, policy makers, and the public is vital to effective water resources management (Wheater and Gober, 2015). Water resource managers provide a crucial link in restoration projects, and by using creative stakeholder engagement mechanisms, they can increase ecological success and stakeholder satisfaction (Druschke and Hychka, 2015). The research community also has a growing responsibility in water resource communication. New perspectives on science communication and the growing role of the researcher and the science can be seen in the push toward greater science accessibility (e.g., open-access publishing), dynamic data visualizations (e.g., NASA's Perpetual Ocean, https://www.nasa.gov/topics/earth/features/perpetual-ocean.html, and Rivers of the Mississippi Watershed, https://svs.gsfc.nasa.gov/4493), and a greater expectation for identifying broader impacts of research. The idea of scientists as active participants, rather than solely as knowledge holders, engaging in the process along with managers and other local stakeholders, may also support a more effective discourse.

In efforts to achieve genuinely sustainable freshwater management, the conversation has necessarily broadened to more deliberately incorporate social and cultural values. For example, the sciences of sociohydrology, which examines the coevolution of people and water systems (Sivapalan et al., 2012), and ethnohydrology, which explores the cultural knowledge of water (Gartin et al., 2010), have begun to seek a better understanding of coupled human-water systems and the cultural and spiritual connections to water by integrating the physical and social sciences. Environmental psychology has emerged to seek to identify the societal connections to aquatic resources, and indicates this knowledge can reduce conflict and facilitate better governance (Walker-Springett et al., 2016). Traditional and local ecological knowledge can also provide valuable insights, adding to the understanding of natural systems and inspiring adaptive management strategies (Berkes et al., 2000).

Management of freshwater resources might also be enhanced if multidisciplinary collaborations (i.e., "team science") extend across geographical and political boundaries. For example, mounting scientific evidence now promotes coordinating conservation efforts across jurisdictional boundaries and spatio-temporal scales given the dramatic economic and ecological efficiencies gained through such management approaches (Neeson et al., 2015). Openly accessible and understandable systematic literature reviews and establishment of communities that encourage knowledge exchange should be available to decision-makers as they negotiate and make compromises in project development (Cvitanovic et al., 2015). Organizations such as university extension offices, environmental advocacy groups, and citizen science programs can help achieve greater stakeholder interaction and involvement, and enhance communication and collaboration across disciplines.

Meeting the challenge of interacting threats in freshwater ecosystems

Human activities result in complex interactions between multiple threats that often lead to unexpected ecological responses and novel ecosystems. Therefore, it is critical that we increase our understanding of the relationships between threats, improve our ability to predict ecological outcomes of interacting threats, and develop management strategies that can accommodate uncertainty, build resistance, and enhance the resilience of freshwater ecosystems.

Despite imperfect knowledge, multiple lines and levels of evidence are available to understand the dimensions of threats; quantify their contribution to alterations, ecological interactions, and effects; and ultimately inform management decisions. Evidence can be drawn from laboratory experiments, artificial freshwater ecosystems, partially nested or replicated field experiments, and meta-analysis of large datasets ("big data") generated by global advances in satellite, mapping, geophysical and monitoring data sources. New statistical approaches for causal inference, Bayesian networks, and expert elicitation can support interpretation of chains of causality, and novel conceptual frameworks that integrate complex interactions can be used to guide testable hypotheses in laboratory and field-based experiments, as well as adaptive management strategies. Expanding the focus on metrics of ecosystem function (e.g., metabolism, nutrient processes, secondary production) and the use of trait-based metrics that link structural and functional responses to characterize and forecast cumulative ecosystem responses would also be advantageous.

In novel ecosystems, we can apply lessons learned from prior endeavors and adopt adaptive and hierarchical approaches to reduce uncertainty through experimental management. At the same time, we should be aware that, as a result of intensification of threats and interaction of alterations, the ecosystem states that form our perception of a baseline or reference condition may change, and our expectations about plausible management outcomes may need to be adjusted. Novel ecosystems may also provide new or unexpected ecosystem services as a result of threat interactions (e.g., the ability of one threat to moderate the adverse effects of another), and the ecosystem states that we wish to conserve in the future will depend upon the value that we assign to those services.

A multi-pronged approach might be essential to ensuring a better future for freshwater ecosystems. Maintaining existing policies and regulations can provide ecosystem protections while research necessary on multiple threats continues and new knowledge is incorporated into policies and regulations. Ongoing and effective public education will create future conservation stewards capable of recognizing environmental emergencies that demand rapid management response. An enhanced ability to identify conservation actions that have multiple benefits will help us to uncover potentially replicable management solutions and maintain positivity as we are increasingly faced with complex management challenges. Finally, we can assemble multidisciplinary research-management teams that use an optimistic lens to look to the future and innovate approaches for addressing predicted challenges (e.g., managing for extremes, future invasions, and a growing population) while supporting desired ecosystem values and services in multi-threat ecosystems.

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Competing interests

JDO is an Associate Editor of the Elementa Ecology knowledge domain; he was not involved in the peer-review of this manuscript. The authors have no other competing interests to declare.

Author contributions

Coordinated project and finalized manuscript for submission: LSC; Contributed to project development: LSC, JDO; Contributed to conception, writing, revision: LSC, JDO, AHA, SE, CPH, JJK, TAK, BMM, EJR, AHR, DLS, JLT, AOW, MSW; Drafted figures: LSC, JDO, AOW

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