Biological Conservation 249 (2020) 108698

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Review

Moving from decision to action in conservation science

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ARTICLE INFO

Keywords:
Decision analysis
Evidence-based
Knowledge co-production
Natural resource management
Research-implementation gap
Translational ecology

ABSTRACT

Biodiversity loss is a major threat to the integrity of ecosystems and is projected to worsen, yet the path to successful conservation remains elusive. Decision support frameworks (DSFs) are increasingly applied by resource managers to navigate the complexity, uncertainty, and differing socio-ecological objectives inherent to conservation problems. Most published conservation research that uses DSFs focuses on analytical stages (e.g., identifying an optimal decision), making it difficult to assess and learn from previous examples in a conservation practice context. Here, we (1) evaluate the relationship between the application of decision science and the resulting conservation outcomes, and (2) identify and address existing barriers to the application of DSFs to conservation practice. To do this, we develop a framework for evaluating conservation initiatives using decision science that emphasizes setting attainable goals, building momentum, and obtaining partner buy-in. We apply this framework to a systematic review of amphibian conservation decision support projects, including a follow-up survey of the pertinent conservation practitioners, stakeholders, and scientists. We found that all projects identified optimal solutions to reach stated objectives, but positive conservation outcomes were limited when implementation challenges arose. Further, we identified multiple barriers (e.g., dynamic and hierarchical leadership, scale complexity, limited resource availability) that can inhibit the progression from decision identification to action implementation (i.e., 'decision-implementation gap'), and to successful conservation outcomes. Based on these results, we provide potential actionable steps and avenues for future development of DSFs to facilitate the transition from decision to action and the realization of conservation successes.

1. Introduction

Biodiversity loss is outpacing global efforts to conserve imperiled species and populations (Butchart et al., 2010; Hoffmann et al., 2010; Johnson et al., 2017). One third of terrestrial vertebrate species are declining (Ceballos et al., 2017) despite the commitment of global resources to address this problem, which includes the protection of 15% of terrestrial habitats (Butchart et al., 2015) and annual conservation spending of more than $20 billion USD (Waldron et al., 2013). To move conservation forward, it is necessary to evaluate existing conservation tools and initiatives to ensure that common obstacles are addressed and successful strategies are identified and emulated (Godet and Devictor, 2018; Schmidt et al., 2019).

Conservation problems are inherently complex, in part because policy and management decisions are not constrained solely by financial resources, but also by non-monetary factors, such as stakeholder interests, system uncertainty, and complex governance structures (Folke et al., 2005; Game et al., 2014). Threats to biodiversity are projected to worsen as human populations continue to grow (Tilman et al., 2017), forcing trade-offs in the use of resources that are available for conservation (Gerber, 2016). In an effort to evaluate and discern among trade-offs, it may be beneficial to consider 'with whom?', 'for

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https://doi.org/10.1016/j.biocon.2020.108698
Received 31 January 2020; Received in revised form 29 June 2020; Accepted 3 July 2020

what?', and 'where and when?' to efficiently and effectively allocate available resources (Schwartz et al., 2018). One particularly useful approach for incorporating the complexity and socio-ecological dynamics of conservation problems is decision science.

Decision science uses rigorous analytical processes to improve decision making by blending behavioral, management, and quantitative sciences (Gregory et al., 2012). Decision support frameworks (DSFs) and their associated tools support conservation actions by explicitly incorporating scientific uncertainty and stakeholder values in a way that leads to transparent, rigorous, and defensible decisions (Margules and Pressey, 2000; Schwartz et al., 2018; Rose et al., 2019). A variety of these frameworks (e.g. structured decision making, open standards, systematic conservation planning; Schwartz et al., 2018) and tools have been developed and are increasingly used by conservation scientists and practitioners (Bower et al., 2018), particularly within state and federal natural resource agencies (e.g., McGowan et al., 2015; Smith et al., 2018). For instance, these tools can be used to identify which scientific uncertainties need to be addressed (Runge et al., 2011), answer large-scale prioritization questions (Ball et al., 2009), and synthesize shared objectives from stakeholders with diverse values and perspectives (Nyumba et al., 2018). DSFs can assist land management agencies in efforts ranging from single-species conservation initiatives (Smith et al., 2018) to maintaining biological and ecological integrity (Wurtzebach and Schultz, 2016).

While references to DSFs and associated tools have grown over the past two decades (Fig. 1), there are few published examples demonstrating that this approach has led to conservation success (i.e., desired outcomes; Westgate et al., 2013; Fabricius and Cundill, 2014; Wong-Parodi et al., 2020). Many conservation projects that use decision science do not yield insights about the conservation utility and challenges of using DSFs because publications focus on the identification of an optimal action, rather than on the implementation of the action and subsequent biological responses. Additionally, the complexities inherent to conservation problems may lead to ambiguous and unclear metrics of conservation success, impeding evaluation of the efficacy of proposed conservation solutions (Game et al., 2014; Rose et al., 2018). To improve the conservation utility of decision science, an integrated framework for explicitly considering the goals of, and connections between, decision science (e.g., identification of optimal actions; Gregory and Keeney, 2002) and conservation (e.g., species recovery and the maintenance of biodiversity; Kareiva and Marvier, 2012) is needed.

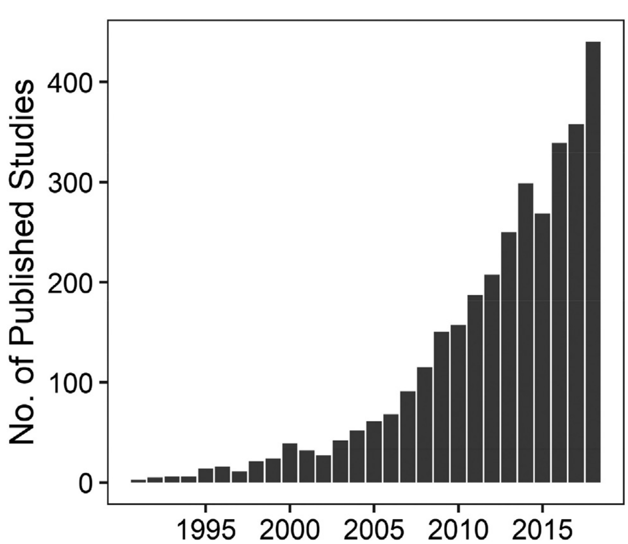

Fig. 1. Web of Science search for the number of published studies between 1991 and 2018 using the following search terms; [(decision science OR decision analysis OR decision support OR decision tool OR structured decision making) AND (biodiversity OR wildlife) AND (conservation)].

Clearly defining the extent of conservation success resulting from DSFs and, more importantly, pinpointing the cause of conservation failures and successes remains a central problem for research scientists, resource managers, and land management agencies (Game et al., 2014).

A systematic review linking DSFs with conservation outcomes can lead to evidence-based insights to more effectively tackle the ongoing biodiversity crisis (Sutherland et al., 2004; Godet and Devictor, 2018). The accountability and defensibility of conservation decisions may be improved by documenting how decision processes and resulting conservation actions have been effective (Bottrill and Pressey, 2012), and will not limit learning to anecdotes (Sutherland et al., 2004; Ferraro and Pattanayak, 2006). Acomprehensive evaluation can help identify the challenges and solutions essential for the effective use of decision science in future conservation efforts (Schwartz et al., 2018; Catalano et al., 2019).

Our objectives are to assess the conservation outcomes that result from the application of decision science, and identify and address the current gaps and limitations in the use of decision science to conservation. Here, we (1) synthesize the goals of decision science and conservation practice to outline a unified framework for evaluating the conservation successes of DSFs (recognizing both organizational and biological limitations and gains), (2) evaluate the outcomes of applied DSF case studies using a review of published literature and follow-up surveys of the conservation practitioners, decision makers, and scientists in each study, (3) synthesize findings from the case study evaluations to identify common barriers that might be mitigated in future decision processes, and (4) outline strategies to better align decision science with conservation practice moving forward to ensure better conservation outcomes.

2. Evaluation of decision science in conservation

2.1. Evaluation framework

We describe a framework to define and evaluate the outcomes of conservation DSFs (Box 1), which synthesizes elements of decision science (Gregory and Keeney, 2002; Guisan et al., 2013; Schwartz et al., 2018) and conservation practice (Fig. 2a; Kapos et al., 2008; Washington et al., 2015). This integrated approach acknowledges that successful conservation does not always require more science (McDonald-Madden et al., 2010), and that good science alone does not ensure conservation success (Toomey et al., 2017). Similarly, it acknowledges that a good decision does not ensure a desired outcome (Howard, 1988). Further, it recognizes that identifying the goal and arriving at a conservation decision is a process that provides a robust foundation for broad conservation success (e.g., species recovery, maintaining or restoring biological integrity, etc.), but also presents opportunities for intermediate successes (e.g., stating clear objectives, developing stakeholder relationships, etc.). Finally, while definitions of success may be perceived as ambiguous due to the complexity in conservation problems (Game et al., 2014), we divide the decision planning and implementation processes into multiple sequential steps and outcomes to provide a checklist of actionable items describing the integration of decision science into conservation.

2.2. Study system

We used amphibian conservation case studies to investigate the barriers and opportunities for success, and to identify pathways to improve future research-practice partnerships. Like many taxa, amphibians are vulnerable to a variety of major threats including climate change, habitat fragmentation, disease, invasive species, and contaminants (Hof et al., 2011), which have led to amphibian declines worldwide (Grant et al., 2016). Threats from multiple stressors, a biphasic life cycle, and substantial data deficiencies (Stuart et al., 2004) for many species generate unavoidable uncertainty and complexity

Box 1

A multi-step approach to evaluate conservation decision support frameworks, which integrates elements of both decision science and conservation practice as previously recognized by Gregory and Keeney (2002), Kapos et al. (2008), Guisan et al. (2013), Washington et al. (2015), and Schwartz et al. (2018):

1. *Identify Key Leadership*
   The person(s) and/or organization(s) with the authority to make a decision, or who serve as a proxy for that decision maker, was identified and involved throughout the decision process.
2. *Frame Problem*
   The trigger that instigated the need to make a decision was recognized and clearly defined. Legal, financial, and/or political constraints were incorporated into a problem statement, along with the spatial and temporal bounds of the decision.
3. *Engage Stakeholders*
   Stakeholders (those parties that are affected by or can affect a decision; e.g. consumers, NGOs, governmental agencies, political officials, businesses, scientists, etc.; Conroy and Peterson, 2013) were explicitly identified, their interests were considered, and their representatives were engaged in the decision process.
4. *Articulate Objective(s)*
   All management objectives were articulated, assigned well-defined metrics (i.e., ways to measure success; also called performance measures, milestones, etc.), and explicitly considered throughout the process.
5. *Specify Potential Action(s)*
   All potential management action(s) that were expected to address the objective(s) were specified.
6. *Develop Predictive Model(s)*
   Models were developed and confronted with data to make predictions about the system state of interest in relation to all potential management action(s). The sources and magnitude of uncertainty present within the decision were identified and incorporated into the modelling process.
7. *Identify Optimal Action(s)*
   An optimal action or strategy was identified among a suite of potential actions by considering the trade-offs among objectives, uncertainty, and legal, political, or financial constraints (using a decision support tool; e.g., consequence table, decision tree, sensitivity analysis, dynamic programming, etc.).
8. *Commit Resources*
   Financial, staffing, and/or equipment resources were made available to implement the identified optimal action or strategy.
9. *Implement Action(s)*
   The identified optimal action or strategy was implemented to the extent of the spatial and temporal bounds of the problem.
10. *Achieve Objective(s)*
    The management objectives were achieved, as determined by the well-defined metrics accompanying each objective.
11. *Achieve Near-Term Conservation Success*
    There was documented progress (i.e. directional) towards conservation success. We define near-term conservation success as: "increasing the likelihood of persistence of native ecosystems, habitats, species, and/or populations in the wild (without adverse effects on human well-being)" (Kapos et al., 2008).
12. *Maintain or Restore Biological Integrity*
    Biological integrity was defined and used in framing the decision support framework, and was restored or maintained at the spatial and temporal scales of interest. We use the U.S. Fish and Wildlife Service definition of biological integrity: "biotic composition, structure, and functioning at genetic, organism, and community levels comparable with historic conditions, including the natural biological processes that shape genomes, organisms, and Communities" (National Wildlife Refuge System Improvement Act of 1997; USFWS, 2001).

when confronting amphibian conservation problems. While DSFs has been used for a variety of amphibian conservation decisions, there are few published examples documenting "successful" management interventions resulting from the process (Canessa et al., 2019b). For these reasons, global amphibian conservation efforts are a model system for yielding insights about the application of DSFs, and these lessons can then be translated to other taxa and systems.

2.3. Systematic review methods

We searched Google Scholar and Web of Science databases for relevant amphibian conservation case studies that reported the use of decision science. The search was limited to peer-reviewed journals and grey literature, but did not include theses or dissertations, book chapters, or conference papers. On 10 and 11 of June 2019, we used the search terms 'amphibian* AND conservation AND decision support' and 'amphibian* AND conservation AND structured decision making' and reviewed the first 20 pages of Google Scholar search results (n = 200 citations), and all items in Web of Science (n = 51 citations) since 1990. Additionally, we reviewed all Structured Decision Making Workshop white papers submitted to the U.S. Fish and Wildlife Service's National Conservation Training Center (n = 53 citations; accessed on 11 June 2019; https://training.fws.gov/courses/ALC/ALC3159/reports/index.html). We searched the literature cited from each of our identified studies for additional relevant articles that were not originally identified in the web-based searches. From this overall collection, we compiled a list of studies that specifically applied a DSF or similar tool (as defined in Schwartz et al., 2018) to a real-world amphibian conservation problem (i.e., not a hypothetical decision context).

In total, we identified 12 case studies (Table 1) that met the criteria above. We reviewed each case study to assess the completion of each step in our evaluation framework (Box 1). Many of the case studies were published after a model had been developed or an optimal decision had been identified, but before an action was implemented or biological outcomes were realized. Thus, in addition to reviewing the published literature, we sent a follow-up questionnaire to all authors of each case study. The questionnaire asked participants to provide information describing the current status of the project, realized or expected conservation outcomes, barriers to the project, and their perception of the role of science during each step of the framework in their project (Supporting Information 1). The coding system, explicit definitions of each step, and questionnaire were all developed prior to evaluating any of the literature or distributing the questionnaire. We followed best practices in designing and implementing questionnaires in biological fields (e.g., White et al., 2005; Crandall et al., 2018), and this study was given approval from the Michigan State University Institutional Review Board (#00002940).

ADW and RFB independently reviewed the literature and questionnaire responses to categorize the completion of each step as either:

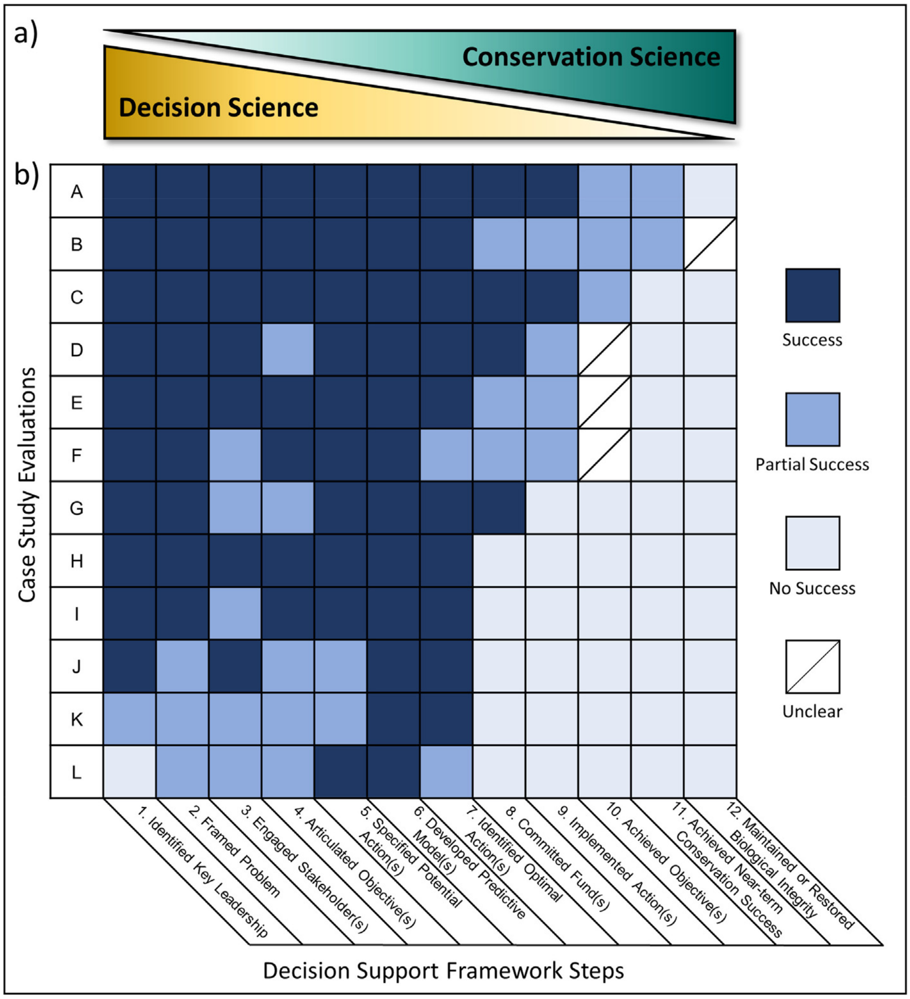

Fig. 2. (a) Ordinal relationship of decision science and conservation science, and (b) evaluations of each step in the evaluation framework (Box 1) for each of the 12 amphibian conservation case studies (Table 1). Colors in boxes indicate whether each step was successful (dark blue) partially successful (medium blue), unsuccessful (light blue), or where outcomes were unclear (diagonal lines through white boxes). Letters describing individual case studies do not correspond to the order of case studies in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
The case studies evaluated for our study that applied a decision support framework to an amphibian conservation problem.

Primary literature	Location	Decision context
Bailey et al., 2008	Mid-Atlantic Region, USA	Develop an adaptive management framework to guide management of vernal pool habitats on federal lands for obligate amphibian species.
Canessa et al., 2014	Southeastern Australia	Optimize the release strategies of the reintroduction program for the endangered southern corroboree frog, *Pseudophryne corroboree*.
Canessa et al., 2016	Southeastern Australia	Determine the appropriate in situ and ex situ management strategies for the recovery efforts of the endangered spotted tree frog, *Litoria spenceri*.
Canessa et al., 2019a	Apennine Mountains, Italy	Develop an adaptive management framework to guide the reintroduction efforts for the endangered European yellow-bellied toad, *Bombina variegata pachypus*.
Gerber et al., 2018	Southern Rocky Mountains, USA	Identify conservation strategies to reduce the Bd-associated declines of the boreal toad, *Anaxyrus boreas boreas*.
Grant et al., 2014	Shenandoah National Park, Virginia, USA	Identify management strategies for the federally endangered Shenandoah salamander, *Plethodon shenandoah*, under projected climate change.
Grant et al., 2013	Chesapeake & Ohio Canal National Historical Park, Maryland, USA	Identify short-term solutions to manage declines of the lentic amphibian community.
Kissel et al., 2017	British Columbia, Canada	Optimize the population supplementation for the federally endangered Oregon spotted frog, *Rana pretiosa*.
O'Donnell et al., 2015	St. Marks National Wildlife Refuge, Florida, USA	Develop an adaptive management program to guide habitat restoration and population recovery efforts for the federally endangered frosted flatwoods salamander, *Ambystoma cingulatum*.
Robinson et al., 2016	Alabama, USA	Guide land acquisition efforts to protect habitat of the federally endangered Red Hills salamander, *Phaeognathus hubrichti*.
Rose et al., 2016	Melbourne, Victoria, Australia	Identify cost-effective management strategies for the endangered growling grass frog, *Litoria raniformis*, under projected urbanization scenarios.
Walls et al., 2015	Southeast Region, USA	Design a captive breeding and release program for the federally endangered flatwoods salamanders, *Ambystoma bishopi* and *A. cingulatum*.

(1) a success, (2) a partial success, (3) no success, or (4) unclear, using the explicit definitions of each step as documented in Box 1. For example, the response: “Yes, successful breeding has been documented at a few of the reintroduction sites, but has not been documented consistently at other reintroduction sites across the range” to question 11: “Was there measurable progress towards conservation success considering the spatial and temporal extent of the decision problem? If yes, please describe or highlight the project successes that support your response” was considered a “partial success” as the respondent reported evidence to confirm an increase in the likelihood of species persistence, but only to a limited spatial extent. Two independent reviewers were used to ensure the consistency and precision of the application of the coding system used in the evaluations (following the approach in Bernard and Grant, 2019). The participants self-reported their position in the case study as one of the following: decision maker (agency decision maker or their proxy), decision analyst (facilitator or analyst), expert (subject matter expert or scientist), or stakeholder (relevant individual or party that could affect or be affected by the decision). We received 37 responses to the follow-up questionnaire from the 80 potential authors (46.25% response rate, and at least one response for each case study). For confidentiality concerns, while we report categories of success for case studies, we do not provide actual responses and we do not identify which categories of success correspond to which case studies (e.g., case studies in Appendix 1 or Table 1 do not correspond to letters in Fig. 2).

3. Lessons learned

3.1. Case study evaluations

Our combined literature review and author questionnaire indicated that ultimate achievement of conservation success was elusive in most of the case studies, which was largely driven by the incompletion of intermediate steps in the process (Fig. 2b). No case study was clearly identified to have maintained or restored the biological integrity of the focal species and/or system specified in the conservation problem (i.e., achieving step 12; Fig. 2b). Two of the twelve case studies reported that they demonstrated the partial achievement of near-term conservation success (step 11) at the time of the survey, three case studies partially achieved, or anticipated partially achieving, their stated objectives, and three case studies were unclear (step 10). The lack of success in this step in other case studies was mostly driven by the lack of action implementation, as only two case studies reported that actions were fully implemented (an additional four case studies partially) to the extent of the conservation problem (step 9). Action implementation was reported to be difficult because of the inability of most case studies to fully commit resources (step 8), despite almost all of the case studies (10 of 12) successfully identifying optimal actions for their respective decision problems (step 7). In some instances, linguistic and scientific uncertainty led to a breakdown in participant buy-in to the decision process in this step (e.g., case studies K and L in Fig. 2b).

Evidence of clear success was more common in the first seven steps, when decision science played a direct role in the process (Fig. 2a). All case studies developed and used predictive models to incorporate risk, uncertainty, and the values of decision makers and stakeholders into the decision context (step 6). Most case studies ($n = 10$) specified a sufficient set of potential actions expected to achieve the stated objectives (step 5). Two case studies (J and K, Fig. 2b) were unable to identify a sufficient set of management actions because of the high level of uncertainty (i.e., data deficiency) within their systems. Seven case studies identified and articulated all management objectives necessary to consider given the decision problem (step 4). Seven case studies included or engaged pertinent stakeholders (step 3), and the remaining five case studies did not include some important stakeholder groups. The decision problem was correctly framed (e.g., temporal and spatial bounds of each problem) by 9 of 12 case studies (step 2), and key leadership was identified and included throughout the process for 10 case studies (step 1). The role and level of engagement of key leadership varied by case study, from primary decision makers to proxy decision makers that had the approval or support of a primary decision maker.

Overall, the application and implementation of a structured, stepwise DSF enabled conservation practitioners and scientists to identify optimal actions or strategies to achieve a stated conservation objective. While the DSFs provided *usable* science in all case studies (i.e. developed predictive models and identified optimal actions), only half of the case studies directly *used* the science (i.e. committed funds and implemented actions), resulting in fewer projects realizing positive conservation outcomes (i.e. achieved management objectives or near-term conservation successes; Fig. 2b) at the time of the survey. Our case study evaluations suggest that the proper engagement and inclusion of decision makers and stakeholders is critical to ensuring the commitment of funds and implementation of optimal actions. We hereafter refer to the successful determination, but lack of implementation, of optimal actions as the ‘decision-implementation gap’.

Using a structured, stepwise process enabled participants within each case study to evaluate and reflect on the status and progress of their project, and identify when a lack of information, stakeholder involvement, or financial support led to conservation priorities not being achieved; participants can use these insights to inform their next conservation problem (Catalano et al., 2019). In the next several sections, we further discuss the following insights synthesized from the case study evaluations: unexpected organizational benefits that resulted from the DSF (Section 3.2 Organizational gains), differences in the perceived and actual roles of science in decision making (Section 3.3 The role of science in DSFs), and barriers that led to the ‘decision-implementation gap’ and limited the likelihood of achieving conservation goals (Section 3.4 Barriers to success).

3.2. Organizational gains

Decision support frameworks (DSFs) provide a process that is transparent, deliberative, and reproducible, and make clear connections between actions and values-based objectives. They can identify an optimal action across multiple, and often competing, objectives, accommodate uncertainty, and include diverse values from stakeholders (Conroy and Peterson, 2013). As we show, DSFs can also yield insights about the decision (e.g., stating clear objectives, delineating jurisdictional boundaries, etc.) and can create and strengthen stakeholder relationships and partnerships (Keeney, 2004; Bennett et al., 2019). For example, multiple respondents across four case studies indicated that participating in a formal application of a DSF improved interpersonal relationships and communication among conservation partners from multiple agencies and institutions. Additionally, respondents from three case studies indicated that their study served as a proof of concept (e.g., by determining an optimal action) and encouraged action in other jurisdictional boundaries (e.g., states, municipalities, etc.) outside the scope of their decision context. In one project, the process contributed to a U.S. Fish and Wildlife Service Species Status Assessment and a listing decision under the U.S. Endangered Species Act. While difficult to formally quantify, the benefits from these types of organizational gains may reach far beyond the discrete case studies in which the participants were involved.

3.3. The role of science in DSFs

When making values-based decisions, science has several discrete roles. First, science (via a statistically robust monitoring program; Nichols and Williams, 2006) may inform whether a decision needs to be made (i.e., if resource status is at undesired levels). Next, science produces predictive models to link actions with values-based objectives (which also incorporate legal and other related constraints). Finally, identification of optimal strategies (by incorporating decision maker

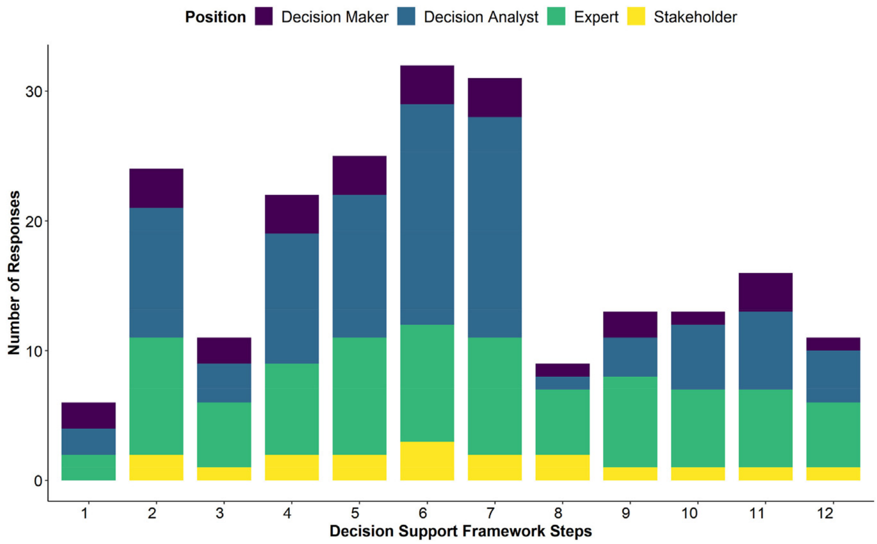

Fig. 3. Respondent viewpoints on where science played a critical role within the decision making process summarized across the 12 amphibian conservation case studies (Table 1). Bars indicate the total number of respondents that thought science played a critical role for each step, colors indicate the responses from the different self-reported positions. Positions include: Decision maker = agency decision maker or their proxy (n = 4); Decision analyst = facilitator or analyst (17); Expert = subject matter experts or scientists (9); Stakeholder = relevant individuals or parties included in the decision making process (3).

and stakeholder values) requires evaluation of model output (Conroy and Peterson, 2013). Though scientific research is a necessary element in making robust conservation management decisions, a misunderstanding of its specific role in decision making can contribute to failed conservation outcomes (Gregory et al., 2006).

We asked participants to report in which steps (Box 1) they thought science played a significant role in their conservation decision making process (Fig. 3). Overall, decision makers and subject matter experts were more likely to believe that science was used in all 12 steps, whereas decision analysts believed that science was used in articulating objectives, developing actions and predictive models, and identifying optimal actions post analysis [steps 4–6]. Interestingly, stakeholders also consistently believed science was involved in most steps, except in step 1, when identifying key leadership.

One of the likely reasons why decision makers, stakeholders and subject matter experts assume science plays a role in each step is that scientists are often the first to detect and signal the alarm for a particular conservation issue. Scientists may also subsequently spearhead the development of DSFs, sometimes as both a decision analyst and team coordinator. Because of this, the distinct roles and professional identities necessary to maximize efficiency of a multi-objective decision problem can become indistinct. If scientists try to represent both scientific (as an analyst and/or subject matter expert) and leadership (as a facilitator and/or coordinator) roles, it may compromise their representation as a neutral and honest broker to stakeholders and decision makers and potentially lead to a distrust or break down of the overall process (Rantala et al., 2017). Further, the misconception of the role of scientific research in a decision making context may isolate the decision science process from the wider political, social, and economic circles in which it is meant to be embedded. Therefore, to maximize the incorporation of values-based judgements, science should be maintained within the discrete bounds that enable natural resource management decisions to be made holistically.

3.4. Barriers to success

Through our questionnaire and evaluation of the case study outcomes (Fig. 2b), we identified a set of barriers to conservation success that we expect to be common in complex conservation decision problems. These barriers include: dynamic and hierarchical leadership, scale complexity, limited resource availability, uncertainty and unpredictability, delayed action, and differing incentive systems.

3.4.1. Dynamic and hierarchical leadership

Leadership structures are both dynamic and hierarchical, and it may be difficult to consistently involve key decision makers throughout the process. Proxy decision makers may be used to represent the interests and values of ultimate decision makers, but because leadership often spans multiple levels of organization (e.g., refuge managers, species recovery coordinators, regional directors, etc.) in complex governance networks with other management agencies and stakeholders, accurate and adequate representation over time may be difficult (Hertin et al., 2009). Further, the lack of direct participation of the ultimate decision makers may limit their buy-in to the final recommended action. Additionally, many case studies experienced staff turnover throughout the conservation project, which may limit the consistent engagement and interest of key personnel (Johnson et al., 2015).

3.4.2. Scale complexity

The spatial and temporal complexity of conservation problems can be large, necessitating the involvement of multiple decision makers at different stages of defining and solving the conservation problem. This may lead to a lack of clear leadership and uncertainty about the ultimate decision-making authority. Case study participants noted this difficulty when the coordination of multiple federal and state agencies was necessary to commit resources or implement actions. This may also make it difficult to evaluate conservation success when the achievement of objectives is expected to be beyond administrative timescales (typically annually or on 5-year cycles for federal programs; Government Performance and Results Act of 1993). Considering objectives over longer horizons without benchmarks in which short-term progress can be measured may hinder the ability of conservation practitioners to demonstrate intermediate successes as milestones to larger conservation investments (Kapos et al., 2008).

3.4.3. Limited resource availability

Resources may not be consistently available to effectively implement actions. Many respondents reported declining budgets, multiple demands on available resources, and lack of buy-in and engagement from senior leadership beyond the decision team (i.e. political or administrative), which reflects the broader lack of resources for conservation (e.g., less than 25% of resources specified in endangered species recovery plans are allocated annually in the United States; Gerber, 2016). None of the case studies had a formal commitment of resources from decision makers at the start of the decision framing process. As a result, resources were most often sought following the decision process via grants or other external sources. No case studies indicated that they were able to guarantee the resources necessary for long-term action, and many identified this as a major concern moving forward.

3.4.4. Uncertainty and unpredictability

High levels of uncertainty can prevent resource managers from implementing the optimal decision, given many decision makers demonstrate low risk tolerance. Many conservation problems are accompanied by a risk of adverse outcomes, which may come from either management inaction or the implementation of an action with potential for harmful effects (Gregory and Long, 2009). For instance, the uncertainty related to the potential impacts of management actions (adverse impacts on other aspects of the ecological system) and insufficient data on the current system state (e.g., population levels) necessitate the formal inclusion of uncertainty and risk in a decision analysis. Additionally, the unpredictability and stochasticity of catastrophic weather events, such as drought, wildfire, hurricanes, and flooding, may impact ongoing and future conservation actions. For example, the success of the implementation of conservation actions was limited due to the overriding negative effects of a major hurricane system in one case study. There have been significant advancements in conservation planning to allow for the prediction of long-term climate change impacts (McDonald-Madden et al., 2011; Reside et al., 2018), but there are existing challenges to integrate the likelihood of severe and unpredictable weather events (Maxwell et al., 2019).

3.4.5. Delayed action

The focus of conservation efforts is often reactive to immediate management problems rather than proactive to broad conservation objectives. No case study successfully maintained or restored biological integrity, an ultimate objective of most federal land management agencies (Wurtzebach and Schultz, 2016). This is not unexpected given that the majority of these case studies cited that this was not one of their explicit objectives or within the temporal or spatial bounds of the decision problem, as they were reacting to immediate and severe species declines. It is more difficult to effectively manage rapidly declining species as opposed to proactive conservation (e.g., increased risk of extinction and increased expenses; Sterrett et al., 2019), and therefore the maintenance or restoration of biological or ecological integrity may be more elusive in these cases.

3.4.6. Differing incentive systems

The different incentive systems used to evaluate the success of scientists and practitioners within their respective organizations may paradoxically lead to unproductive conservation outcomes. For example, the decision maker in one of the case studies stated a perception that the scientists were more interested in the novel aspects of the associated publication than in solving the manager's decision problem. Scientists in multiple case studies perceived the hesitancy of managers to implement any actions to be attributed to a fear of failure, even though key uncertainties were explicitly incorporated into the decision analysis to ensure an optimal decision would be robust to the scientific uncertainties. The occurrence of this type of conflict is not wholly unexpected given the institutional constraints of both scientists and conservation practitioners (Knight et al., 2008; Hallett et al., 2017; Merkle et al., 2019).

3.4.7. Summary of barriers

Our results suggest that the lack of successful completion of all steps in the DSF results from barriers that were not strictly analytical or biological, but more so related to the complexity of the governance structures for a given decision problem. Other similar studies have cited institutional barriers as the most frequent or major reason to explain limited integration of science into conservation programs (Cvitanovic et al., 2016; Rose et al., 2018). Multiple studies have also found that decision making agencies with internal technical expertise and capacity or technocratic decision makers were more likely to incorporate translational science into policy and management processes (Lemos, 2008; Tang and Dessai, 2012). Collectively, these findings highlight and emphasize the challenges of integrating scientific research into different scales of governance and policy-making, economic structures, and social-cultural dynamics.

3.5. The broader research-practice interface

The use of decision science in conservation is driven by the broader need of evidence-based policy and management, which necessitates stronger connections between the end-users of scientific information to the researchers who generate it (Meadow et al., 2015; Enquist et al., 2017). This reflects growing recognition that the traditional production of applied research is insufficient to solve pressing, real-world problems (Knight et al., 2008). Our study synthesizes insights from real-world applications of DSFs to highlight and improve the effectiveness of the use of decision science to solve conservation management problems.

Throughout our evaluations, we saw the generation of *usable* science across all case studies, but *used* science and subsequent positive conservation outcomes were less common when implementation challenges arose. This decision-implementation gap often resulted from failing to properly engage stakeholders and decision makers early in the DSF process or from implementation challenges following the identification of optimal actions. While translational science is being operationalized across multiple institutions to better connect research and practice, the broader cultures of those institutions, particularly the long-term planning and funding, have been slow to change (Holzer et al., 2019). Decision science can appropriately incorporate the uncertainty associated with complex ecological systems into optimization methods, but it is more difficult to account for the profound complexity and uncertainty of the socio-political systems in which they try to inform (Hertin et al., 2009; Clark et al., 2016).

In summary, decision making is not done in a vacuum. It is both enveloped and influenced by the wider social, political, and economic circles in which power and authority reside (van Kerkhoff and Lebel, 2015). The framework for decision science provides a direct and transparent way to incorporate complex socio-cultural processes within the broader research-practice interface (Knight et al., 2008; Rose et al., 2019). However, our findings suggest that science and society are not always effectively linked, and that the application of decision science to conservation problems can be improved. To strengthen the application of DSFs in conservation decision making, we outline potential steps and avenues for future research and development below.

4. Realignment of decision science & conservation practice

Scientists are often tasked with developing DSFs and tools to help managers and agencies navigate complex conservation problems, with the explicit goal of identifying and supporting actions that address a set of defined objectives (Gregory and Keeney, 2002). Engaging in a formal decision process should result in improved conservation outcomes, but the presence of biological and management uncertainties (Nicol et al., 2019) and institutional constraints (Johnson et al., 2015) may result in decisions that fail to achieve conservation goals. Through our questionnaire and case study evaluations (Section 3.1), we identified barriers that hinder the conservation success that should result from the application of decision science to resource management (Section 3.4), which include: dynamic and hierarchical leadership, scale complexity, limited resource availability, uncertainty and unpredictability, delayed action, and differing incentive systems. These barriers were most likely to hinder the commitment of resources and the implementation of actions across case studies (Fig. 2b). Considering these barriers, in the following sections, we (1) outline potential actionable steps to build a stronger connection between decision science and conservation practice, and (2) identify areas for further development to address the gaps in the existing set of decision support tools, frameworks, and methods applied in conservation science.

4.1. Potential actionable steps

When confronting a complex conservation problem, resource managers may be advised to use decision science to help identify the best management option, and then implement the recommended decision. Our results indicate a considerable disconnect between these two processes. To bridge this decision-implementation gap, we provide the following suggestions:

(1) *Clearly outline the expectations of involvement for all relevant decision makers and construct detailed communication plans*, recognizing that key leadership needs to be engaged in a way that transcends organizational structures and may involve multiple actors across space and time. If the person with ultimate authority for a decision cannot be fully engaged early in the decision process and instead defers to a proxy or representative, establishing a formal communication plan at the beginning of the process may improve stakeholder engagement. This can keep the process transparent and ensure that the recommended action is acceptable to the decision makers and stakeholders (Wall et al., 2017a).
(2) *Include measurable attributes that coincide with near-term data collection but also inform long-term objectives.* The evaluation of objectives in many of the case studies were considered over long time horizons (> 50 years to perpetuity). However, those time scales do not align with program evaluation timeframes (e.g., typically annual or 5-year cycles; Government Performance and Results Act of 1993), strategic planning, or funding cycles. Either framing the decision to be more in line with these timeframes, or specifying measurable attributes of objectives to align with shorter term horizons can help identify obstacles early on, demonstrate near-term successes, build project momentum, and maintain consistent conservation investment (Kapos et al., 2008; Lawson et al., 2017).
(3) *Clearly outline resource commitments and sources when identifying and engaging key leadership.* Management cost may be considered as an objective in a decision analysis (e.g., "minimize cost") or, less commonly, as a constraint (e.g., "annual costs must not exceed…"). Specifying a cost objective may improve creativity when brainstorming potential actions. However, being clear about project resources from the outset may be beneficial in setting realistic objectives and correctly evaluating tradeoffs with the cost objective. If resources cannot be guaranteed, or if sources are unknown during the problem framing, consider framing the problem statement to include the goal of securing resources to implement the recommended actions (e.g., writing grants, fundraising).
(4) *Incorporate boundary organizations and individuals to champion the process forward.* After identifying an optimal decision, implementing it requires a leader who will keep participants accountable and move the process forward (Walters, 2007). Boundary organizations are formal institutions that facilitate collaborations across diverse disciplines (Guston, 2001). They can link scientists, managers, and policymakers through academic units (e.g., Center for Biodiversity Outcomes; Gerber and Raik, 2018), governmental divisions (e.g., National Park Service Inventory and Monitoring Networks; Fancy et al., 2009), established task forces (e.g., endangered species recovery teams; Miller et al., 1994), and administrative working groups (e.g., U. S. Fish and Wildlife Flyway Councils; Boere and Stroud, 2006). Boundary organizations are often well-suited to assume the responsibility of organizing the participants in a conservation decision, ensure effective communication and translation of technical information and stakeholder input, and help develop useful research products and decision making aids (Kirchhoff et al., 2013; Meadow et al., 2015; Safford et al., 2017).
(5) *Develop and facilitate a translational culture early on among project collaborators* (Hallett et al., 2017). Success in science-management partnerships is often improved when scientists communicate with decision makers early, well before a decision needs to be made (Merkle et al., 2019). Our framework (Box 1) can be used as a checklist to build stronger working partnerships and ensure project buy-in. Science-management partnerships broadly, and DSFs specifically, may be (incorrectly) conceptualized as a conservation decision relay, with each party completing their own leg of the race in isolation from other collaborators. We suggest structuring collaborations more akin to team cycling races, in which all riders stick together, but each rider takes regular stints as the lead, allowing other team members to "draft" off the leader who pulls the rest of the team along to the next stage. This style emphasizes continuous communication, the constant inclusion of multiple parties, and the use of team member's skills at the appropriate times (Mosher et al., 2020).

While decision science is meant to navigate complex governance networks and socio-cultural dynamics, these are still very difficult processes to navigate. Our potential actionable steps are meant to address the difficulties of navigating complex governance networks and socio-cultural dynamics with the formal application of a decision support framework. This approach recognizes that a decision involves both values and information, which occur in discrete but connected steps (Gregory et al., 2006).

4.2. Future development

Decision science is a valuable tool for confronting conservation problems (Rose et al., 2019). However, there are still shortcomings in its practical application to conservation. Further development and consideration regarding how to overcome these limitations will help to fully realize the potential benefits of decision science for conservation.

First, while conservation decision making occurs within a socio-ecological context and specifies values-based objectives germane to a problem, decisions are often made without the explicit integration of social science research (Holzer et al., 2019). Decision science can be improved by better and more consistently incorporating social science theory, methods, or data, and by directly including social scientists (Robinson et al., 2019). Not only can the integration of social science help understand and quantify the values and objectives of stakeholders, it can also build broader theories to explain the perception and behavior of actors that lead to implementation challenges (Lawson et al., 2017).

Second, as our results demonstrate, decision science successfully produces usable science with stakeholder and decision maker support. However, we need to better identify and explore how complex organizations disseminate and adopt new information (Taylor, 1991). By understanding these mechanisms, we can better incorporate the complexity and dynamics of organizations and governance networks, and facilitate the flow and evaluation of information. These advancements are necessary to ensure the use and implementation of decision science results (Wall et al., 2017b).

Finally, there are many methods and techniques that have been developed to implement decision support frameworks, and to conduct translational science more broadly. However, the formal training and education of ecologists to apply these methods has lagged (Fuller et al., 2020). The training of conservation scientists and practitioners to improve evidence-based decision making could now be a key priority in graduate education and professional development moving forward (Clark et al., 2016; Schwartz et al., 2017).

5. Conclusions

Conservation biology is a complex discipline, which must incorporate elements of social science, biological research, and economics for conservation initiatives to be successful. Contemporary conservation problems include potentially devastating outcomes and high uncertainty – characteristics of 'wicked' problems (Game et al., 2014) – making conservation actions all the more urgent. To solve these problems, decision science provides tools for identifying timely and effective conservation actions (Margules and Pressey, 2000; Schwartz et al., 2018; Rose et al., 2019). Although the application of DSFs in conservation has increased, few examples demonstrate that DSFs lead to desired conservation outcomes (Westgate et al., 2013; Fabricius and Cundill, 2014), which limits our learning to anecdote (Sutherland et al., 2004). The conservation community is currently in a position to synthesize common challenges faced in decision making, and to incorporate this knowledge into future conservation initiatives.

We generated a new framework for evaluating conservation success on a continuum, which emphasizes attainable goals that allow for intermediate and stepwise successes, building momentum, and obtaining partner buy-in (Jagannathan et al., 2020). This framework can also be used by scientists, stakeholders, and resource managers as a checklist for working towards conservation goals and creating valuable working partnerships. We applied this framework to evaluate the application of DSFs in past amphibian conservation case studies, which generated novel insights on, and proposed solutions to, the barriers that impede the achievement of conservation objectives. Overall, our work evaluated the links between DSFs and conservation outcomes, and has led us to evidence-based suggestions that will better tackle the current biodiversity crisis (Sutherland et al., 2004; Godet and Devictor, 2018). This synthesis moves us one step towards addressing the current gaps and limitations in applying decision science to conservation (Rose et al., 2018), and ultimately, moving from decisions to actions.

CRediT authorship contribution statement

Alexander D. Wright: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing - original draft, Project administration. **Riley F. Bernard**: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing - original draft. **Brittany A. Mosher**: Conceptualization, Validation, Writing - original draft. **Katherine M. O'Donnell**: Conceptualization, Validation, Writing - original draft. **Taylor Braunagel**: Conceptualization, Investigation, Writing - review & editing. **Graziella V. DiRenzo**: Investigation, Writing - original draft. **Jill Fleming**: Conceptualization, Investigation, Writing - review & editing. **Charles Shafer**: Conceptualization, Investigation, Writing - review & editing. **Adrianne B. Brand**: Conceptualization, Writing - review & editing. **Elise F. Zipkin**: Writing - review & editing, Supervision. **Evan H. Campbell Grant**: Conceptualization, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are incredibly grateful to all the survey respondents for providing their professional opinions. This is Contribution Number 756 of the U.S. Geological Survey Amphibian Research and Monitoring Initiative (ARMI). Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The authors declare no conflicts of interest. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. This study was approved by the Michigan State University Institutional Review Board (IRB #00002940).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2020.108698.

References

Bailey, L.L., Nichols, J.D., Green, A.W., Grant, E.H.C., Hogan, D.M., Knutson, M.G., Lang, M.W., Mattfeldt, S.D., Obrecht, H., Converse, S.J., Runge, M.C., 2008. Managing Vernal Pool Habitats on Federal Lands: Maintaining Obligate Amphibian Species. USGS Patuxent Wildlife Research Center, Laurel, MD, USA.

Ball, I.R., Possingham, H.P., Watts, M., 2009. Marxan and relatives: software for spatial conservation prioritisation. In: Moilanen, A., Wilson, K.A., Possingham, H.P. (Eds.), Iin Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools. Oxford University Press, Oxford, UK, pp. 185–195 Chapter 14.

Bennett, N.J., Di Franco, A., Calò, A., Nethery, E., Niccolini, F., Milazzo, M., Guidetti, P., 2019. Local support for conservation is associated with perceptions of good governance, social impacts, and ecological effectiveness. Conservation Letters, e12640. https://doi.org/10.1111/conl.12640.

Bernard, R.F., Grant, E.H.C., 2019. Identifying common decision problem elements for the management of emerging fungal diseases of wildlife. Soc. Nat. Resour. 32 (9), 1040–1055. https://doi.org/10.1080/08941920.2019.1610820.

Boere, G.C., Stroud, D.A., 2006. The flyway concept: what it is and what it isn't. In: Boere, G.C., Galbraith, C.A., Stroud, D.A. (Eds.), Waterbirds Around the World. The Stationery Office, Edinburgh, UK, pp. 40–47.

Bottrill, M.C., Pressey, R.L., 2012. The effectiveness and evaluation of conservation planning. Conserv. Lett. 5 (6), 407–420. https://doi.org/10.1111/j.1755-263x.2012.00268.x.

Bower, S.D., Brownscombe, J.W., Birnie-Gauvin, K., Ford, M.I., Moraga, A.D., Pusiak, R.J., ... Bennett, J.R., 2018. Making tough choices: picking the appropriate conservation decision-making tool. Conservation Letters 11 (2), e12418. https://doi.org/10.1111/conl.12418.

Butchart, S.H., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J.P., Almond, R.E., ... Carpenter, K.E., 2010. Global biodiversity: indicators of recent declines. Science 328 (5982), 1164–1168. https://doi.org/10.1126/science.1187512.

Butchart, S.H., Clarke, M., Smith, R.J., Sykes, R.E., Scharlemann, J.P., Harfoot, M., ... Brooks, T.M., 2015. Shortfalls and solutions for meeting national and global conservation area targets. Conservation Letters 8 (5), 329–337. https://doi.org/10.1111/conl.12158.

Canessa, S., Hunter, D., McFadden, M., Marantelli, G., McCarthy, M.A., 2014. Optimal release strategies for cost-effective reintroductions. J. Appl. Ecol. 51 (4), 1107–1115. https://doi.org/10.1111/1365-2664.12253.

Canessa, S., Converse, S.J., West, M., Clemann, N., Gillespie, G., McFadden, M., ... McCarthy, M.A., 2016. Planning for ex situ conservation in the face of uncertainty. Conservation Biology 30 (3), 599–609. https://doi.org/10.1111/cobi.12613.

Canessa, S., Ottonello, D., Rosa, G., Salvidio, S., Grasselli, E., Oneto, F., 2019a. Adaptive management of species recovery programs: a real-world application for an endangered amphibian. Biol. Conserv. 236, 202–210. https://doi.org/10.1016/j.biocon.2019.05.031.

Canessa, S., Spitzen-van der Sluijs, A., Martel, A., Pasmans, F., 2019b. Mitigation of amphibian disease requires a stronger connection between research and management. Biol. Conserv. 236, 236–242. https://doi.org/10.1016/j.biocon.2019.05.030.

Catalano, A.S., Lyons-White, J., Mills, M.M., Knight, A.T., 2019. Learning from published project failures in conservation. Biol. Conserv. 238, 108223. https://doi.org/10.1016/j.biocon.2019.108223.

Ceballos, G., Ehrlich, P.R., Dirzo, R., 2017. Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. Proc. Natl. Acad. Sci. 114 (30), E6089–E6096. https://doi.org/10.1073/pnas.1704949114.

Clark, W.C., Van Kerkhoff, L., Lebel, L., Gallopin, G.C., 2016. Crafting usable knowledge for sustainable development. Proc. Natl. Acad. Sci. 113 (17), 4570–4578. https://doi.org/10.1073/pnas.1601266113.

Conroy, M.J., Peterson, J.T., 2013. Decision Making in Natural Resource Management: A Structured, Adaptive Approach. John Wiley & Sons.

Crandall, S.G., Ohayon, J.L., de Wit, L.A., Hammond, J.E., Melanson, K.L., Moritsch, M.M., ... Packard, H.G., 2018. Best practices: social research methods to inform biological conservation. Australasian Journal of Environmental Management 25 (1), 6–23. https://doi.org/10.1080/14486563.2017.1420499.

Cvitanovic, C., McDonald, J., Hobday, A.J., 2016. From science to action: principles for undertaking environmental research that enables knowledge exchange and evidence-based decision-making. J. Environ. Manag. 183, 864–874. https://doi.org/10.1016/j.jenvman.2016.09.038.

Enquist, C.A., Jackson, S.T., Garfin, G.M., Davis, F.W., Gerber, L.R., Littell, J.A., ... Hiers, J.K., 2017. Foundations of translational ecology. Frontiers in Ecology and the Environment 15 (10), 541–550. https://doi.org/10.1002/fee.1733.

Fabricius, C., Cundill, G., 2014. Learning in adaptive management: insights from published practice. Ecol. Soc. 19 (1).

Fancy, S.G., Gross, J.E., Carter, S.L., 2009. Monitoring the condition of natural resources in US national parks. Environ. Monit. Assess. 151 (1–4), 161–174.

Ferraro, P.J., Pattanayak, S.K., 2006. Money for nothing? A call for empirical evaluation of biodiversity conservation investments. PLoS Biol. 4 (4), e105. https://doi.org/10.

1371/journal.pbio.0040105.
Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of social-ecological systems. Annu. Rev. Environ. Resour. 30, 441–473. https://doi.org/10.1146/annurev.energy.30.050504.144511.
Fuller, A.K., Decker, D.J., Schiavone, M.V., Forstchen, A.B., 2020. Ratcheting up rigor in wildlife management decision making. Wildl. Soc. Bull. 44 (1), 29–41. https://doi.org/10.1002/wsb.1064.
Game, E.T., Meijaard, E., Sheil, D., McDonald-Madden, E., 2014. Conservation in a wicked complex world; challenges and solutions. Conserv. Lett. 7 (3), 271–277. https://doi.org/10.1111/conl.12050.
Gerber, L.R., 2016. Conservation triage or injurious neglect in endangered species recovery. Proc. Natl. Acad. Sci. 113 (13), 3563–3566. https://doi.org/10.1073/pnas.1525085113.
Gerber, L.R., Raik, D., 2018. Conservation science needs new institutional models for achieving outcomes. Front. Ecol. Environ. 16 (8), 438–439. https://doi.org/10.1002/fee.1951.
Gerber, B.D., Converse, S.J., Muths, E., Crockett, H.J., Mosher, B.A., Bailey, L.L., 2018. Identifying species conservation strategies to reduce disease-associated declines. Conserv. Lett. 11 (2), e12393. https://doi.org/10.1111/conl.12393.
Godet, L., Devictor, V., 2018. What conservation does. Trends Ecol. Evol. 33 (10), 720–730. https://doi.org/10.1016/j.tree.2018.07.004.
Government Performance and Results Act of 1993, Pub. L. No. 103-62.
Grant, E.H.C., Zipkin, E.F., Nichols, J.D., Campbell, J.P., 2013. A strategy for monitoring and managing declines in an amphibian community. Conserv. Biol. 27 (6), 1245–1253. https://doi.org/10.1111/cobi.12137.
Grant, E.H.C., Wofford, J.E.B., Smith, D.S., Dennis, J., Hawkins-Hoffman, C., Schaberl, J., Foley, M., Bogle, M., 2014. Management and monitoring of the endangered Shenandoah salamander under climate change: workshop report 10–12 April 2012. In: Natural Resource Report NPS/SHEN/NRR—2014/867. National Park Service, Fort Collins, Colorado.
Grant, E.H.C., Miller, D.A., Schmidt, B.R., Adams, M.J., Amburgey, S.M., Chambert, T., ... Johnson, P.T., 2016. Quantitative evidence for the effects of multiple drivers on continental-scale amphibian declines. Scientific Reports 6, 25625.
Gregory, R.S., Keeney, R.L., 2002. Making smarter environmental management decisions. J. Am. Water Resour. Assoc. 38 (6), 1601–1612. https://doi.org/10.1111/j.1752-1688.2002.tb04367.x.
Gregory, R., Long, G., 2009. Using structured decision making to help implement a precautionary approach to endangered species management. Risk Analysis: An International Journal 29 (4), 518–532. https://doi.org/10.1111/j.1539-6924.2008.01182.x.
Gregory, R., Failing, L., Ohlson, D., McDaniels, T.L., 2006. Some pitfalls of an over-emphasis on science in environmental risk management decisions. Journal of Risk Research 9 (7), 717–735. https://doi.org/10.1080/13669870600799895.
Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., Ohlson, D., 2012. Structured Decision Making: A Practical Guide to Environmental Management Choices. John Wiley & Sons.
Guisan, A., Tingley, R., Baumgartner, J.B., Naujokaitis-Lewis, I., Sutcliffe, P.R., Tulloch, A.I., ... Martin, T.G., 2013. Predicting species distributions for conservation decisions. Ecology Letters 16 (12), 1424–1435. https://doi.org/10.1111/ele.12189.
Guston, D.H., 2001. Boundary organizations in environmental policy and science: an introduction. Sci. Technol. Hum. Values 26 (4), 399–408.
Hallett, L.M., Morelli, T.L., Gerber, L.R., Moritz, M.A., Schwartz, M.W., Stephenson, N.L., ... Woodhouse, C.A., 2017. Navigating translational ecology: creating opportunities for scientist participation. Frontiers in Ecology and the Environment 15 (10), 578–586. https://doi.org/10.1002/fee.1734.
Hertin, J., Turnpenny, J., Jordan, A., Nilsson, M., Russel, D., Nykvist, B., 2009. Rationalising the policy mess? Ex ante policy assessment and the utilisation of knowledge in the policy process. Environ Plan A 41 (5), 1185–1200. https://doi.org/10.1068/a40266.
Hof, C., Araújo, M.B., Jetz, W., Rahbek, C., 2011. Additive threats from pathogens, climate and land-use change for global amphibian diversity. Nature 480 (7378), 516.
Hoffmann, M., Hilton-Taylor, C., Angulo, A., Böhm, M., Brooks, T.M., Butchart, S.H., ... Darwall, W.R., 2010. The impact of conservation on the status of the world's vertebrates. Science 330 (6010), 1503–1509. https://doi.org/10.1126/science.1194442.
Holzer, J.M., Adamescu, C.M., Cazacu, C., Díaz-Delgado, R., Dick, J., Méndez, P.F., ... Orenstein, D.E., 2019. Evaluating transdisciplinary science to open research-implementation spaces in European social-ecological systems. Biological Conservation 238, 108228. https://doi.org/10.1016/j.biocon.2019.108228.
Howard, R.A., 1988. Decision analysis: practice and promise. Manag. Sci. 34 (6), 679–695. https://doi.org/10.1287/mnsc.34.6.679.
Jagannathan, K., Arnott, J.C., Wyborn, C., Klenk, N., Mach, K.J., Moss, R.H., Sjostrom, K.D., 2020. Great expectations? Reconciling the aspiration, outcome, and possibility of co-production. Curr. Opin. Environ. Sustain. 42, 22–29. https://doi.org/10.1016/j.cosust.2019.11.010.
Johnson, F.A., Boomer, G.S., Williams, B.K., Nichols, J.D., Case, D.J., 2015. Multilevel learning in the adaptive management of waterfowl harvests: 20 years and counting. Wildl. Soc. Bull. 39 (1), 9–19. https://doi.org/10.1002/wsb.518.
Johnson, C.N., Balmford, A., Brook, B.W., Buettel, J.C., Galetti, M., Guangchun, L., Wilmshurst, J.M., 2017. Biodiversity losses and conservation responses in the Anthropocene. Science 356 (6335), 270–275. https://doi.org/10.1126/science.aam9317.
Kapos, V., Balmford, A., Aveling, R., Bubb, P., Carey, P., Entwistle, A., ... Walpole, M., 2008. Calibrating conservation: new tools for measuring success. Conservation Letters 1 (4), 155–164. https://doi.org/10.1111/j.1755-263X.2008.00025.x.
Kareiva, P., Marvier, M., 2012. What is conservation science? BioScience 62 (11), 962–969. https://doi.org/10.1525/bio.2012.62.11.5.
Keeney, R.L., 2004. Making better decision makers. Decis. Anal. 1 (4), 193–204. https://doi.org/10.1287/deca.1040.0009.
van Kerkhoff, L.E., Lebel, L., 2015. Coproductive capacities: rethinking science-governance relations in a diverse world. Ecol. Soc. 20 (1). https://doi.org/10.5751/ES-07188-200114.
Kirchhoff, C.J., Lemos, M.C., Dessai, S., 2013. Actionable knowledge for environmental decision making: broadening the usability of climate science. Annu. Rev. Environ. Resour. 38. https://doi.org/10.1146/annurev-environ-022112-112828.
Kissel, A.M., Palen, W.J., Govindarajulu, P., 2017. A decision-theory approach to cost-effective population supplementation for imperiled species. Ecol. Econ. 142, 194–202. https://doi.org/10.1016/j.ecolecon.2017.06.028.
Knight, A.T., Cowling, R.M., Rouget, M., Balmford, A., Lombard, A.T., Campbell, B.M., 2008. Knowing but not doing: selecting priority conservation areas and the research–implementation gap. Conserv. Biol. 22 (3), 610–617. https://doi.org/10.1111/j.1523-1739.2008.00914.x.
Lawson, D.M., Hall, K.R., Yung, L., Enquist, C.A., 2017. Building translational ecology communities of practice: insights from the field. Front. Ecol. Environ. 15 (10), 569–577. https://doi.org/10.1002/fee.1736.
Lemos, M.C., 2008. What influences innovation adoption by water managers? Climate information use in Brazil and the United States 1. JAWRA Journal of the American Water Resources Association 44 (6), 1388–1396. https://doi.org/10.1111/j.1752-1688.2008.00231.x.
Margules, C.R., Pressey, R.L., 2000. Systematic conservation planning. Nature 405 (6783), 243.
Maxwell, S.L., Butt, N., Maron, M., McAlpine, C.A., Chapman, S., Ullmann, A., ... Watson, J.E., 2019. Conservation implications of ecological responses to extreme weather and climate events. Diversity and Distributions 25 (4), 613–625. https://doi.org/10.1111/ddi.12878.
McDonald-Madden, E., Baxter, P.W., Fuller, R.A., Martin, T.G., Game, E.T., Montambault, J., Possingham, H.P., 2010. Monitoring does not always count. Trends Ecol. Evol. 25 (10), 547–550. https://doi.org/10.1016/j.tree.2010.07.002.
McDonald-Madden, E., Runge, M.C., Possingham, H.P., Martin, T.G., 2011. Optimal timing for managed relocation of species faced with climate change. Nature Climate Change 1 (5), 261–265.
McGowan, C.P., Smith, D.R., Nichols, J.D., Lyons, J.E., Sweka, J., Kalasz, K., ... Spear, B., 2015. Implementation of a framework for multi-species, multi-objective adaptive management in Delaware Bay. Biological Conservation 191, 759–769. https://doi.org/10.1016/j.biocon.2015.08.038.
Meadow, A.M., Ferguson, D.B., Guido, Z., Horangic, A., Owen, G., Wall, T., 2015. Moving toward the deliberate coproduction of climate science knowledge. Weather, Climate, and Society 7 (2), 179–191. https://doi.org/10.1175/WCAS-D-14-00050.1.
Merkle, J.A., Anderson, N.J., Baxley, D.L., Chopp, M., Gigliotti, L.C., Gude, J.A., ... Mong, T.W., 2019. A collaborative approach to bridging the gap between wildlife managers and researchers. The Journal of Wildlife Management. https://doi.org/10.1002/jwmg.21759.
Miller, B., Reading, R., Conway, C., Jackson, J.A., Hutchins, M., Snyder, N., ... Derrickson, S., 1994. A model for improving endangered species recovery programs. Environmental Management 18 (5), 637–645.
Mosher, B.A., Bernard, R.F., Lorch, J.M., Miller, D.A., Richgels, K.L., White, C.L., Campbell Grant, E.H., 2020. Successful molecular detection studies require clear communication among diverse research partners. Front. Ecol. Environ. 18 (1), 43–51. https://doi.org/10.1002/fee.2141.
National Wildlife Refuge System Improvement Act of 1997, Pub. L. No. 105-57, 111 Stat. 1252.
Nichols, J.D., Williams, B.K., 2006. Monitoring for conservation. Trends Ecol. Evol. 21 (12), 668–673. https://doi.org/10.1016/j.tree.2006.08.007.
Nicol, S., Brazill-Boast, J., Gorrod, E., McSorley, A., Peyrard, N., Chadès, I., 2019. Quantifying the impact of uncertainty on threat management for biodiversity. Nat. Commun. 10 (1), 1–14.
Nyumba, T.O., Wilson, K., Derrick, C.J., Mukherjee, N., 2018. The use of focus group discussion methodology: insights from two decades of application in conservation. Methods Ecol. Evol. 9 (1), 20–32. https://doi.org/10.1111/2041-210X.12860.
O'Donnell, K.M., Walls, S.C., Johnson, F.A., Martin, J., Romanach, S.S., Gorman, T.A., Messerman, A.F., Mitchell, H.G., Mott, J., Peacock, T., Reinman, J., Semlitsch, R.D., Titus, G., Smith, D.R., 2015. An Adaptive Management Approach to Habitat Restoration and Population Recovery of Flatwoods Salamanders: A Case Study from the Structured Decision Making Workshop. National Conservation Training Center, U.S. Fish & Wildlife Service, Shepherdstown, WV.
Rantala, L., Sarkki, S., Karjalainen, T.P., Rossi, P.M., 2017. How to earn the status of honest broker? Scientists' roles facilitating the political water supply decision-making process. Soc. Nat. Resour. 30 (10), 1288–1298. https://doi.org/10.1080/08941920.2017.1331484.
Reside, A.E., Butt, N., Adams, V.M., 2018. Adapting systematic conservation planning for climate change. Biodivers. Conserv. 27 (1), 1–29. https://doi.org/10.1007/s10531-017-1442-5.
Robinson, O.J., McGowan, C.P., Apodaca, J.J., 2016. Decision analysis for habitat conservation of an endangered, range-limited salamander. Anim. Conserv. 19 (6), 561–569. https://doi.org/10.1111/acv.12275.
Robinson, K.F., Fuller, A.K., Stedman, R.C., Siemer, W.F., Decker, D.J., 2019. Integration of social and ecological sciences for natural resource decision making: challenges and opportunities. Environ. Manag. 63 (5), 565–573. https://doi.org/10.1007/s00267-019-01141-2.
Rose, L.E., Heard, G.W., Chee, Y.E., Wintle, B.A., 2016. Cost-effective conservation of an endangered frog under uncertainty. Conserv. Biol. 30 (2), 350–361. https://doi.org/10.1111/cobi.12626.
Rose, D.C., Sutherland, W.J., Amano, T., González-Varo, J.P., Robertson, R.J., Simmons,

B.I., ... Wu, W., 2018. The major barriers to evidence-informed conservation policy and possible solutions. Conservation Letters 11 (5), e12564. https://doi.org/10.1111/conl.12564.

Rose, D.C., Amano, T., González-Varo, J.P., Mukherjee, N., Robertson, R.J., Simmons, B.I., ... Sutherland, W.J., 2019. Calling for a new agenda for conservation science to create evidence-informed policy. Biological Conservation 238, 108222. https://doi.org/10.1016/j.biocon.2019.108222.

Runge, M.C., Converse, S.J., Lyons, J.E., 2011. Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. Biol. Conserv. 144 (4), 1214–1223. https://doi.org/10.1016/j.biocon.2010.12.020.

Safford, H.D., Sawyer, S.C., Kocher, S.D., Hiers, J.K., Cross, M., 2017. Linking knowledge to action: the role of boundary spanners in translating ecology. Front. Ecol. Environ. 15 (10), 560–568. https://doi.org/10.1002/fee.1731.

Schmidt, B.R., Arlettaz, R., Schaub, M., Lüscher, B., Kröpfli, M., 2019. Benefits and limits of comparative effectiveness studies in evidence-based conservation. Biol. Conserv. 236, 115–123. https://doi.org/10.1016/j.biocon.2019.05.033.

Schwartz, M.W., Hiers, J.K., Davis, F.W., Garfin, G.M., Jackson, S.T., Terando, A.J., ... Brunson, M.W., 2017. Developing a translational ecology workforce. Frontiers in Ecology and the Environment 15 (10), 587–596. https://doi.org/10.1002/fee.1732.

Schwartz, M.W., Cook, C.N., Pressey, R.L., Pullin, A.S., Runge, M.C., Salafsky, N., ... Williamson, M.A., 2018. Decision support frameworks and tools for conservation. Conservation Letters 11 (2), e12385. https://doi.org/10.1111/conl.12385.

Smith, D.R., Allan, N.L., McGowan, C.P., Szymanski, J.A., Oetker, S.R., Bell, H.M., 2018. Development of a species status assessment process for decisions under the US Endangered Species Act. Journal of Fish and Wildlife Management 9 (1), 302–320. https://doi.org/10.3996/052017-JFWM-041.

Sterrett, S.C., Katz, R.A., Brand, A.B., Fields, W.R., Dietrich, A.E., Hocking, D.J., ... Grant, E.H.C., 2019. Proactive management of amphibians: Challenges and opportunities. Biological Conservation 236, 404–410. https://doi.org/10.1016/j.biocon.2019.05.057.

Stuart, S.N., Chanson, J.S., Cox, N.A., Young, B.E., Rodrigues, A.S., Fischman, D.L., Waller, R.W., 2004. Status and trends of amphibian declines and extinctions worldwide. Science 306 (5702), 1783–1786. https://doi.org/10.1126/science.1103538.

Sutherland, W.J., Pullin, A.S., Dolman, P.M., Knight, T.M., 2004. The need for evidence-based conservation. Trends Ecol. Evol. 19 (6), 305–308. https://doi.org/10.1016/j.tree.2004.03.018.

Tang, S., Dessai, S., 2012. Usable science? The UK climate projections 2009 and decision support for adaptation planning. Weather, Climate, and Society 4 (4), 300–313. https://doi.org/10.1175/WCAS-D-12-00028.1.

Taylor, R.S., 1991. Information use environments. In: Dervin, B., Voigt, M.J. (Eds.), Progress in Communication Science. vol. 10. Ablex, Norwood, NJ, pp. 217–254.

Tilman, D., Clark, M., Williams, D.R., Kimmel, K., Polasky, S., Packer, C., 2017. Future threats to biodiversity and pathways to their prevention. Nature 546 (7656), 73.

Toomey, A.H., Knight, A.T., Barlow, J., 2017. Navigating the space between research and implementation in conservation. Conserv. Lett. 10 (5), 619–625. https://doi.org/10.1111/conl.12315.

U.S. Fish and Wildlife Service, U.S. Fish and Wildlife Service Manual, 601 FW 3.6(B), available at http://policy.fws.gov/manual.html (last visited Apr. 5, 2019); Policy on Maintaining the Biological Integrity, Diversity, and Environmental Health of the National Wildlife Refuge System, 66 Fed. Reg. 3810, 3818 Jan. 16, 2001.

Waldron, A., Mooers, A.O., Miller, D.C., Nibbelink, N., Redding, D., Kuhn, T.S., ... Gittleman, J.L., 2013. Targeting global conservation funding to limit immediate biodiversity declines. Proceedings of the National Academy of Sciences 110 (29), 12144–12148. https://doi.org/10.1073/pnas.1221370110.

Wall, T.U., McNie, E., Garfin, G.M., 2017a. Use-inspired science: making science usable by and useful to decision makers. Front. Ecol. Environ. 15 (10), 551–559. https://doi.org/10.1002/fee.1735.

Wall, T.U., Meadow, A.M., Horganic, A., 2017b. Developing evaluation indicators to improve the process of coproducing usable climate science. Weather, Climate, and Society 9 (1), 95–107. https://doi.org/10.1175/WCAS-D-16-0008.1.

Walls, S.C., Allan, N., Green, A., Keever, A., Messerman, A.F., Fenolio, D., Gorman, T.A., Mitchell, H.G., Mandica, M., Semlitsch, R.D., McGowan, C., 2015. Structured Decision Making for Recovery of Imperiled Flatwoods Salamanders: Minimizing Extinction Risk With Captive Breeding and Population Supplementation. A Case Study From a Structured Decision Making Workshop. National Conservation Training Center, U.S. Fish & Wildlife Service, Shepherdstown, WV.

Walters, C.J., 2007. Is adaptive management helping to solve fisheries problems? AMBIO: A Journal of the Human Environment 36 (4), 304–308. https://doi.org/10.1579/0044-7447(2007)36[304:IAMHTS]2.0.CO;2.

Washington, H., Baillie, J., Waterman, C., Milner-Gulland, E.J., 2015. A framework for evaluating the effectiveness of conservation attention at the species level. Oryx 49 (3), 481–491. https://doi.org/10.1017/S0030605314000763.

Westgate, M.J., Likens, G.E., Lindenmayer, D.B., 2013. Adaptive management of biological systems: a review. Biol. Conserv. 158, 128–139. https://doi.org/10.1016/j.biocon.2012.08.016.

White, P.C., Jennings, N.V., Renwick, A.R., Barker, N.H., 2005. Questionnaires in ecology: a review of past use and recommendations for best practice. J. Appl. Ecol. 42 (3), 421–430. https://doi.org/10.1111/j.1365-2664.2005.01032.x.

Wong-Parodi, G., Mach, K.J., Jagannathan, K., Sjostrom, K.D., 2020. Insights for developing effective decision support tools for environmental sustainability. Curr. Opin. Environ. Sustain. 42, 52–59. https://doi.org/10.1016/j.cosust.2020.01.005.

Wurtzebach, Z., Schultz, C., 2016. Measuring ecological integrity: history, practical applications, and research opportunities. BioScience 66 (6), 446–457. https://doi.org/10.1093/biosci/biw037.