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PERSPECTIVE

Structured decision making remains underused in ecological restoration despite opportunities

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Abstract
Ecological restoration is considered an essential activity as we attempt to repair anthropogenic degradation. Yet, resources are limited and it is important that efforts focus on activities that are effective and yield successful restoration. Structured decision making (SDM) is an organized framework that is designed to incorporate differing values across stakeholders and evaluate alternatives. The SDM framework typically consists of six steps: define the decision problem, define objectives and evaluation criteria, develop alternatives, estimate consequences, evaluate trade-offs, and decide, implement, and monitor. Here, we posit that SDM is well suited for ecological restoration, yet remains underused. Specifically, tools such as stakeholder surveys, conceptual modeling, and multi-criteria decision analysis are notably useful in ecological restoration and can be applied under the SDM framework to ensure robust and transparent decision making. We illustrate the application of SDM to ecological restoration with case studies that used SDM alongside ecosystem service assessments, for species-as-risk management, and to assess action desirability across large and diverse stakeholder groups. Finally, we demonstrate how SDM is equipped to handle many of the challenges associated with ecological restoration by identifying commonalities. We contend that increased use of SDM for ecological restoration by environmental managers has the potential to yield wise use of limited resources and more effective restoration outcomes.

Keywords Restoration ecology · Values · Decision analysis · Cost–benefit · Uncertainty · Project management

1 Introduction

Conservation agencies and organizations are turning to ecological restoration to counter widespread ecological degradation (Aronson and Alexander 2013; Suding et al. 2015) as a means to preserve or improve biodiversity (De Groot et al. 2013). The United Nations (UN) recently launched the Decade for Ecosystem Restoration, emphasizing a global need for, and commitment to, restoration (Aronson et al. 2020). Specifically, the goal of ecological restoration is to reverse or reduce the sources of ecosystem alteration and degradation, where the ultimate goal is to conserve biodiversity (Hobbs and Norton 1996). However, restoration has limitations in that it may be expensive both in terms of cost and time and can carry a risk of failure or even unintended outcomes (Jones and Schmitz 2009) emphasizing the need to maximize efficacy (Young and Schwartz 2019). An additional complication for ecological restoration stems from the underlying motivations and values of involved stakeholders[1]

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1 For the purpose of this paper, we use the term stakeholder in the broadest possible sense (similar to the word "actor"). We explicitly acknowledge that Indigenous communities and governments are not stakeholders but rather rightsholders so our use of the term stakeholder in this paper implicitly includes all relevant actors.

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which can extend beyond science to social factors (Martin et al. 2018). Although some restoration decision guidelines exist (e.g., Clewell et al. 2005; McDonald et al. 2016), there is no broadly applicable framework to help restoration professionals choose among alternative interventions, incorporate factors such as relative values, time and space requirements, costs, public perception, risk of failure, and risk of perverse outcomes. Resorting to ecological restoration without clear objectives based on proven approaches could result in more harm than good (Cooke et al. 2018).

More recently, there have been applications of decision making frameworks including structured decision making (SDM) to complicated environmental problems such as ecological restoration (e.g., Fournier et al. 2023; Sanchez et al. 2023; Keating et al. 2023; Sepulveda et al. 2022; Robinson et al. 2021; Fischer et al. 2022; King et al. 2022). The three main paradigms used in environmental decision making are science-based, consensus-based or economic and multi-criteria based (Gregory et al. 2012). Science-based decision making (e.g., based off modeling) can neglect external factors such as politics or social aspects (Failing et al. 2013). Consensus-based depends on the notion that those involved foresee a "good" end goal and have a thorough understanding of potential alternative options, which is not always the case with complex, environmental problems (Gregory et al. 2012). Finally, economic and multicriteria focus on quantitative and/or cost–benefit analyses, that may leave out creative thinking and stakeholder engagement. Decision making within the context of ecological restoration is particularly complex, as it can be considered a "wicked problem" (Rittel and Webber 1973), whereby differing priorities and values across stakeholders need to be taken into account. Relative to other decision-making paradigms, SDM is particularly suited to encompass these differences in values (Guerrero et al. 2017). However, despite the promise of SDM, it has yet to be used broadly by environmental managers within the context of ecological restoration.

As we face continued loss of biodiversity within the Anthropocene,[2] we argue that SDM could benefit ecological restoration, making wise use of limited resources and maximizing efficacy while taking into account differences in values across involved organizations and stakeholders. In this paper, we first provide a summary of SDM and how it can be used to improve long-term outcomes for biodiversity. To expand on the book by Gregory et al. (2012), we provide an updated and contemporary overview of tools associated with each step of SDM which could be applied throughout the ecological restoration process. To illustrate the utility of SDM and the associated tools within the context of ecological restoration, we provide examples for each of the steps within the framework. Case studies have also been included to illustrate the full SDM framework as it was used for projects related to the restoration of watersheds, wetlands, and sensitive habitats. These case studies highlight use of SDM alongside ecosystem services assessments, for species-at-risk management, and for making desirable decisions with large and diverse groups of stakeholders. We then demonstrate how ecological restoration could benefit from SDM by identifying commonalities.

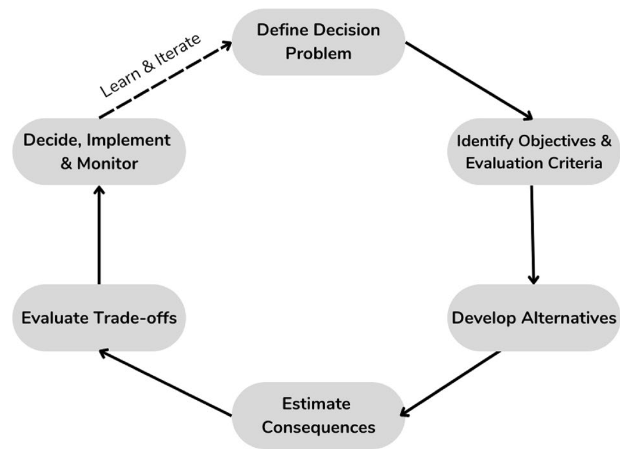

Fig. 1 The steps within the structured decision-making framework that could be applied to ecosystem restoration. Modified from Gregory et al. (2012)

2 A closer look at structured decision making

SDM is a collaborative process that can use an organized approach and tools to clearly set objectives that enhances decision-maker insight and understanding (see Fig. 1; Gregory et al. 2012). Relative to other decision-making frameworks (e.g., consensus-based), SDM includes provisions that incorporate viewpoints from multiple stakeholders, which is common for ecological restoration (Schwartz et al. 2018). Beyond scientific implications, nuances that are considered within the SDM framework include values, consequences, and choices from among multiple alternatives (Wilson and McDaniels 2007). While there are principles for conducting ecological restoration as outlined by the Society for Ecological Restoration (Gann et al. 2019) that share some commonalities with SDM (e.g., engage with a wide range of stakeholders and use measurable indicators to assess efficacy), SDM is not explicitly included in most restoration guidelines.

[2] The Anthropocene currently has no formal status in the Divisions of Geologic Time (https://pubs.usgs.gov/fs/2018/3054/fs20183054.pdf). It is used here to indicate a time when human activities have significant effects on the global environment.

There are typically six key steps within the stepwise SDM process as outlined by Gregory et al. (2012): (1) identify the decision context, (2) define objectives and measures, (3) develop alternatives, (4) estimate consequences, (5) evaluate trade-offs and select a preferred alternative, and (6) implement, monitor, and assess. The first step identifies the problem or question, which organizations and/or stakeholders need to be involved and their associated roles, and the scope of the decision. Next, the goal of step two is to define the objectives of the decision (which may be contradictory across agencies and stakeholders) and outline the benchmarks for what success may look like when comparing potential alternatives (step 3). Potential alternatives to address the problem are developed in the third step, whereby a creative set of actions or strategies can be refined after initial brainstorming. Within the fourth step, each potential alternative is analytically explored to understand the implications in terms of the benchmarks. Further analyses are conducted in the fifth step to determine how potential alternatives can create trade-offs among objectives before choosing among alternatives. Within this step, members are able to voice their concerns and explore preferences in efforts to find ways to make transparent trade-offs and build a shared understanding during decision making. Finally, the last step involves the implementation of the decision and continued monitoring to determine whether the benchmarks were met. Ideally, the last step results in further understanding of implications and uncertainties to aid in future decision-making processes.

3 Applying SDM to ecological restoration

SDM and the associated suite of tools are well suited to mitigate the various challenges and limitations associated with the ecological restoration process for a number of reasons (see Table 1). With ecological restoration, there are often diverse stakeholders with varying objectives and expectations that stem from different values, and SDM is capable of identifying, including, and balancing these differences throughout the framework. In addition to highly technical information derived from biological, chemical, or engineering data, ecological restoration also seeks to include other forms of knowledge (e.g., Indigenous ways of knowing, local ecological knowledge) and SDM has provisions to incorporate these other important resources. Oftentimes ecological restoration can be very complex and alternatives seem endless. SDM provides a means to evaluate the trade-offs and consequences associated with each alternative to select the best outcome. Ecological restoration is a relatively new field (Clewell and Aronson 2012), with many sources of uncertainty (e.g., species can be data deficient, lack of information of historical baselines, diverse responses to different interventions; see Sachs 2023), and SDM can incorporate the estimates of consequences associated with these unknowns and evaluate the effects of uncertainty within the decision. Ecological restoration is faced with many other challenges including limitations regarding budgets, timelines, and resources that ultimately will affect decisions. Throughout the framework, SDM can inject "reality" into the decision, by accounting for these limitations, which maximizes transparency for decision makers. Ecological restoration results in very real consequences such as differences in ecosystem services provided, and SDM can operationalize the consequences and trade-offs associated with each alternative, which can help with understanding implications. Monitoring is essential to further our understanding as a means to better conserve biodiversity (Wortley et al. 2013). SDM is an interactive process that promotes monitoring to make better decisions in the future. Further, both ecological restoration and SDM are inherently forward looking, and combined they could result in better outcomes. Finally, with biodiversity (e.g., endangered species) on the line, ecological restoration is time sensitive. As the framework associated with SDM is structured and formulaic, decisions can be expedited while still maintaining a deliberate process. Although there have been some cases of applying SDM within the context of ecological restoration (e.g., Dalyander et al. 2016; Failing et al. 2013; Guerrero et al. 2017; Kozak and Piazza 2015; Nagarkar and Raulund-Rasmussen 2016), SDM has yet to be widely embraced and some of the associated contemporary tools that have emerged or been refined in recent years remain underused. To provide more context for SDM within the context of ecological restoration, next we explore the application of each step within the framework. Within each step, we provide examples of specific SDM tools and then describe how each step could be applied to benefit ecological restoration.

3.1 Define decision problem

Within the SDM framework, the first step requires the identification of key stakeholders, decision makers, and organizations that should be involved (Fig. 1). This is the foundational, and arguably most important, step in SDM (Gregory et al. 2012; Hammond et al. 2015). Defining the problem can lead to a common understanding of associated links and impacts, as well as uncertainties across stakeholders. Ecological restoration is inherently complex in that it requires expertise on diverse topics (e.g., engineering, biology, hydrology, sociology) and often across multiple jurisdictions (e.g., municipal, provincial/state, federal) at varying spatial scales (e.g., Lin et al. 2019). Additionally, many different types of stakeholders are often involved such as practitioners, policy makers, engineers, Indigenous knowledge and rights holders, local knowledge holders, resource users (e.g.,

Table 1 Challenges of ecological restoration that structured decision making can improve

Challenges of ecological restoration	Justification and SDM context	Relevant SDM steps
Diverse stakeholders involved in ecological restoration can often have competing objectives and expectations stemming from different values (Piczak et al. 2022)	Relative to other decision-making paradigms, SDM is capable of encompassing all values equally through integration of social and ecological science (Robinson et al. 2019)	1. Define decision problem & 2. Identify objectives and evaluation criteria
Ecological restoration needs to incorporate many types of knowledge and information beyond strictly technical (e.g., biological, chemical, engineering; Gann et al. 2019)	Ecological restoration is inherently linked with humans and SDM can provide the framework to incorporate non-scientific types of information such as values, social, and economic factors (Wilson and McDaniels 2007)	2. Identify objectives and evaluation criteria
Ecological restoration is extremely complex and multifaceted with seemingly infinite alternatives (Kibler et al. 2018)	SDM provides tools to develop alternatives, and then quantify the consequences and trade-offs associated with each option (Converse and Grant 2019)	3. Develop alternatives
Budgets, timelines and resources are often limited for ecological restoration (Lapointe et al. 2014)	SDM can take budgets into consideration- operationalizing the allocation of resources, maximizing transparency throughout the steps (Gregory et al 2012)	2. Identify objectives and evaluation criteria, 4. Estimate consequences & 5. Evaluate trade-offs
There are many uncertainties within ecological restoration, with different uncertainties at any given phase that can result in unknown consequences (Palmer & Stewart 2020)	SDM can quantify and weigh uncertainties, resulting in more informed decision making (Dalyander et al. 2016)	5. Estimate consequences
Different restoration alternatives could result in different ecosystem services (Martin et al. 2018)	SDM evaluates and operationalizes trade-offs, while considering all objectives and consequences (such as different ecosystem services; Runge and Bean 2020)	5. Evaluate trade-offs
Monitoring is essential to iteratively advance understanding and refine techniques used for ecological restoration (Block et al. 2001)	SDM promotes monitoring and evaluation to improve the evidence base for future decision making (Lyons et al. 2008)	6. Decide, implement, and monitor
Ecological restoration is inherently forward looking as a means to improve biodiversity and ecosystem services (Choi et al. 2008)	SDM articulates alternatives and promotes learning aimed at choosing the best decision to improve future outcomes (Gregory et al. 2012)	All steps
With biodiversity on the line (potentially including imperiled species), ecological restoration is time sensitive (Luther et al. 2020)	Within ecological restoration, decisions need to occur relatively quickly, the framework associated with SDM can expedite decision making while still maintaining a thorough and deliberate process	All steps

hikers, kayakers, anglers, bird watchers), and/or scientists. Identifying all relevant stakeholders can help reveal uncertainties or gaps in knowledge that may be required to undertake the ecological restoration. An additional key aspect of this stage is outlining legal or regulatory constraints for the project, which can be contributed by specific stakeholders. Throughout the identification of stakeholders, there remains potential to marginalize certain groups resulting in exclusion and increased biases. To mitigate this issue and effectively identify stakeholders, various tools have been proposed. For example, stakeholder analysis (Reed et al. 2009; Conroy and Peterson 2013) which can identify stakeholders, differentiate and subsequently categorize roles and finally, outline the associated relationships among stakeholders.

Identifying who needs to be involved early on in a restoration project is important as this sets the foundation for the next process in this step: defining the problem. This critical step should involve all stakeholders and clarifies the scope, context for the problem, and what decision is being made and why. As all stakeholders should have been identified and included at this point, incorporating the varying perspectives iteratively can help define the problem. Defining the problem can be done with various approaches including brainstorming/conceptual models, futures tools, or status/threat assessments, scenario-mapping, and scoping sessions (see Table 2). In relation to ecological restoration, examples of problems include the source of the stressor imparting damage to an ecosystem (e.g., an invasive species or anthropogenic activity), the decline of a specific species, or the loss of important ecosystem functions or services (e.g., soil formation, pollination, or recreation).

3.2 Identify objectives and evaluation criteria

The second step within the SDM framework is outlining the objectives and evaluation criteria, which collectively define "what matters" across involved stakeholders (Gregory et al. 2012). A key part of this step is the *agreement* of what matters across stakeholders, who may have different goals, expectations, and values. Further, the objectives and criteria provide the foundations for searching for alternatives and a framework for comparing those alternatives. It is important for objectives to be concise, measurable, time-limited, and specific as they form the basis for comparing alternatives in future steps within the SDM framework (Gregory et al. 2012). Clear objectives and pre-defined evaluation criteria are necessary for effective ecological restoration (Gann et al. 2019).

Objectives can be elicited through brainstorming sessions with all stakeholders involved after the problem has been identified (i.e., "what matters"; step 1). Further, while there are many different types of objectives: means and fundamental objectives remain integral to the SDM process. Specifically, fundamental refers to the "why" of problems, and means refers to "how" actions could be achieved (Keeney 1992; Gregory et al. 2012). At this point, various tools could be used to effectively identify objectives including surveys for all stakeholders to identify values (Guerrero et al. 2017) and/or objectives hierarchies (Gregory et al. 2012) which can help identify missing aspects and alternatives (see Table 2). For example, stretch goals and backcasting can be useful in large-scale restoration projects as they are tools which promote defining ends (i.e., fundamental) objectives early on and then working backwards to determine how they are attainable (Table 1; Manning et al. 2006).

Outlining evaluation criteria (also called measurable attributes) will provide the foundation for using a specific metric to measure the progress and performance of objectives (Keeney 1992; Gregory et al. 2012). Evaluation criteria also provide a metric for stakeholders to consistently compare and assess alternatives and ultimately aid in decision making. Across the various and likely diverse stakeholders (especially for ecological restoration), evaluation criteria inherently synthesize extensive technical information or data into a more digestible summary format, which can lead to understanding of performance regardless of expertise or role. Defining evaluation criteria through tools such as conceptual models or means-ends diagrams can provide useful visual representations of overall project goals while condensing the information for clarity (Table 1). Broadly, criteria should be complete, clear, understandable, direct, and operational (Keeney and Gregory 2005).

Objectives for ecological restoration can be highly variable, but can be broadly grouped into three main categories: ecological (e.g., species, ecosystem function, or ecosystem services; Ehrenfeld 2000), social/cultural (e.g., recreational opportunities, aesthetics, or return to previous land use) or economic (e.g., costs of restoration techniques and potential economic benefits or costs for the restored ecosystem). Further, objectives and evaluation criteria are highly dependent on baseline site assessments, which includes the current state of the degraded site and associated deficiencies (Gann et al. 2019). An additional aspect of this stage is the identification of the reference ecosystem, which will subsequently help define the objectives and the degree of recovery required for the target site to reach the reference condition. Conducting baseline site assessments and identifying reference ecosystems will set the bounds of what is desirable and possible (Miller et al. 2017). Without baseline site assessments or reference ecosystems, there would be no measurable comparator to detect changes (i.e., as measured by evaluation criteria) derived from the ecological restoration over time. For ecological restoration, evaluation criteria can include metrics to assess changes for biotic (e.g., biomass of a target species or habitat use), abiotic (e.g., soil composition), chemical (e.g., water quality), or social (e.g., aesthetics or

Table 2 Tools used for ecological restoration used in structured decision making, based on (Hemming et al. 2022)

Structured decision-making step	Tool	Ecological restoration example	References
(1) Define the problem	Stakeholder mapping	Marine conservation planning	Brown et al. 2016
	Scenario-planning	Fisheries management	Gammage and Jarre 2021
	Spatial data	Land-use planning	Jalkanen et al. 2020
	Status assessments	River ecosystem restoration	Lorenz and Feld 2013
	Threat assessments	Species at-risk habitat restoration	Doll et al. 2022
	Scoping sessions	Fish-habitat restoration/Co-production	Piczak et al. 2022
(2) Identify objectives and evaluation criteria	Objectives hierarchy	Watershed restoration/barrier removal	Lin et al. 2019
	Stretch Goals/Backcasting	Large-scale ecological restoration	Manning et al. 2006
	Stakeholder surveys	Terrestrial vegetation restoration	Guerrero et al. 2017
	Means-ends diagrams	Estuary restoration	Gregory and Wellman 2001
	Delphi Techniques	Forest management	Waldron et al. 2016
(3) Develop alternatives	Strategy tables	Salmon population protection	Gregory and Long 2009
	Solution scanning	Forest and forest ecosystem restoration	Hernández-Morcillo et al. 2022
	Conceptual models	Ecosystem management	Harwell et al. 1999
	Spatial data	Multi-species fisheries habitat restoration	Rous et al. 2017
	Sensitivity analysis	Landscape restoration	Demir et al. 2021
	Delphi method	Forest habitat/biodiversity management	Filyushkina et al. 2018
(4) Estimate consequences	Consequence tables	Hydrological regime management	Failing et al. 2013
	Conceptual models	Coastal barrier island restoration	Dalyander et al. 2016
	Evidence synthesis	Fish habitat and stream restoration	Stewart et al. 2009
	Expert elicitation	Pacific salmon recovery	Chalifour et al. 2022
	Quantitative models	Fish translocation and species management	Harig and Fausch 2002
	Leading and Lagging Indicators	Forest restoration	Ota et al. 2021
(5) Evaluate trade-offs	Multi-criteria decision analysis	Watershed restoration planning	Martin et al. 2018
	Multi-objective programming	Agricultural water management	Zhang et al. 2020
	Analytical hierarchy process	Urban stream restoration	Hong and Chang 2020
	Cost–benefit analysis	Temperate forest/stream ecosystem restoration	Acuña et al. 2013
	Cost-Effectiveness analysis	Natural woodland restoration	Macmillan et al. 1998
	Risk assessment	Dam removal/river restoration	Hart et al. 2002
	Decision trees	Vegetation re-establishment	Barnard et al. 2019
	Scenario comparison	Broad application	Metzger et al. 2017
(6) Decisions, implementation, and monitor	Model-based strategizing	Species distribution/habitat restoration	Zellmer et al. 2019
	Communication strategy	Wetland restoration	Martin et al. 2022
	Before-after-control-impact design	Riparian habitat restoration	Muller et al. 2016
	Robustness analysis	Ecological network management	Pocock et al. 2012
	Multifunctionality index	Coastal seagrass bed restoration	Beheshti et al. 2022
	Large-scale spatial monitoring	Large-scale forest restoration	de Almeida et al. 2020
	Electronic tagging	Large-scale habitat use assessment	Lapointe et al. 2013

Example studies that use each of the specified tools have also been provided, although many of these examples use multiple tools that are beneficial to structured decision making and ecological restoration recreation opportunities) aspects. It is crucial to use the same indicators throughout the entirety of the project to provide a fair point of comparison and account for temporal scale.

3.3 Develop alternatives

Relative to other decision-making frameworks, SDM provides more opportunities to incorporate creativity, particularly at step three, which is identifying alternatives. The objectives and evaluation criteria outlined in the previous step should drive the identification and evaluation of alternatives (Gregory et al. 2012). Specifically, alternatives are complete solutions to the problems previously identified, which can be compared by involved stakeholders. There are two main processes within this step, first alternatives need to be identified, which could be achieved through activities such as brainstorming, then the alternatives need to be considered. One main consideration during evaluation of alternatives is whether the proposed actions can achieve the objectives and solve the problem as outlined in previous steps. Further, the potentially diverse preferences and values across stakeholders should be reflected by the creation of a suite of actions designed to achieve different objectives, each of which can be compared and refined. A suite of mutually exclusive alternatives is tangible in that they provide context for stakeholders to think critically while considering options. Broadly, alternatives need to be complete, value-focused, directly comparable and distinguishable (Gregory et al. 2012) and can be either a discrete set of options (e.g., which species to focus efforts on), continuous range of values (e.g., size of habitat to be created), and/or a combination (Runge and Walshe 2014). Tools to identify and compare alternatives include conceptual modeling, Delphi methods, spatial data, strategy tables, sensitivity analyses, and solution scanning (see Table 2). For example, strategy tables allow stakeholders to consider different combinations of actions that could be taken, while solution scanning compares all known options based on evidence and practicality (Sutherland et al. 2014). Sensitivity analyses permit decision makers to understand variations in parameters and uncertainties across alternatives and associated outcomes on the decision model (e.g., Demir et al. 2021). Importantly, although there are methods for comparing alternatives, groups should focus first on creativity and design of alternatives before assessing feasibility.

The number of possible alternatives that could be considered during ecological restoration can be extensive and complicated to say the least (Martin et al. 2018), and SDM can aid in the identification and exploration of these options (Hemming et al. 2022). Budget, size and/or number of sites, techniques used, or species targeted are just a few different examples that could have many alternatives within the ecological restoration process. Additional facets of ecological restoration are the social and economic concerns, which should also be incorporated into alternatives stemming from previously outlined objectives to meet societal demands. SDM provides the tools and processes to not only consider actions that would influence the ecological objectives of a restoration project, but also social and economic objectives through actions such as recreational activities, scenic landscapes, and learning opportunities as described below in the ecological restoration of the Woonasquatucket River watershed, Rhode Island, USA (Martin et al. 2018; for more information please see Case Study #1). Further, restoration ecology as a discipline is relatively new and is the science of iteratively testing alternatives ultimately to further our understanding and by refining and developing techniques to ultimately increase efficacy of efforts (Wyant et al. 1995), for which adaptive management, a special case of SDM for recurrent or sequential decisions, might be appropriate (Williams et al. 2007; Runge 2011; Hunt et al. 2020).

3.4 Estimate consequences

This step of the SDM framework incorporates the objectives developed from step two and the set of alternatives from step three to estimate the consequences/performance of actions that could be taken (Hemming et al. 2022). This step is typically undertaken by ecological or social scientists, traditional ecological knowledge holders or economists with the use of the best available evidence base, data, and predictive tools (see Table 2). Although this step can be quantitative, the different values from stakeholders should have already been incorporated in previous steps (Smith et al. 2020). Further, estimating consequences attempts to predict future events as well as implications, which can help the decision-making process. The consequences should be analyzed using the evaluation criteria that were identified in the second step of the SDM framework. Using the same evaluation criteria across multiple alternatives will provide a comparison point which will aid in decision making.

One important aspect that occurs within this step is quantifying and prioritizing key uncertainties. Identifying uncertainties as early as possible is beneficial in that they can be actioned if possible to decrease knowledge gaps and provide more information for decision making (Gregory et al. 2012). For example, if populations of a target species were unknown, surveys and population modeling could be undertaken as to not hinder the decision-making process. If information for specific uncertainties cannot be mitigated, it should be noted so that these gaps can be accounted for throughout the rest of the SDM. Along with estimating consequences, quantifying (and remediating, if possible) uncertainties can help identify actions that are more robust to these unknowns (Hemming et al. 2022). Sometimes it is not possible to analytically quantify all uncertainties, but providing estimations of upper and lower bounds (e.g., the maximum and minimum population estimates of an endangered species) can be helpful during decision making. Determining the sources and magnitude of uncertainties can enable groups to better understand the risks associated with implementation of specific actions, determine if an uncertainty will change the choice of alternative, and decide if reduction of key uncertainties through adaptive management is feasible and warranted (Runge 2011). Consequence tables contribute to assessing both alternatives and uncertainties against each objective, which can help identify which actions perform the best in terms of evaluation criteria. For example, Failing et al. (2013) used consequence tables to assess the consequences of different flow regimes in a hydrological regime restoration project based on their identified alternative strategies (Table 2). This allowed the group to project the various consequences different flows had across different target species, as not all species would respond the same to changes in streamflow.

Within the context of ecological restoration, there can be extensive alternatives and uncertainties. Fortunately, as restoration ecology is an inherently scientific discipline, it is possible to use a variety of quantitative and predictive tools, which can help prioritize alternatives. These tools can include those designed for prioritizing among locations, threats, or individual actions (e.g., Hanson et al. 2019, 2022). Uncertainties within restoration ecology are prevalent as it is an emerging and growing discipline (Roberts et al. 2009). Quantifying uncertainties is particularly important for ecological restoration as actions taken can have severe implications, particularly for imperiled species (such as insects which are often data deficient) that could be jeopardized by poor decision making; Doll et al. 2022, for more information please see Case Study #2). Further, alternatives for ecological restoration can often incorporate untried management actions, which can introduce another source of uncertainty. Of note, tools like calculating the expected value of perfect information (EVPI, Runge et al. 2011) and constructed value of information (CVOI, Runge et al. 2023) can be used to identify key uncertainties that would change the decision choice and that would benefit most from research to reduce them. Among the possible extensive alternatives and uncertainties within ecological restoration, it is important to move forward with decisions and not retreat to inaction (Converse and Grant 2019), which could result in further damage to the target species or ecosystems.

3.5 Evaluate trade-offs

Across the alternatives identified within step four, there are often trade-offs, which need to be considered prior to decision making. Within this step, it is important to balance differing values in terms of the consequences of potential actions taken and objectives (Gregory and Keeney 2002). Balancing trade-offs can involve reducing uncertainties, managing risks, and predicting implications (Hemming et al. 2022). During this step, maximizing transparency of trade-offs will contribute to deliberation among stakeholders (Runge and Bean 2020). Various types of trade-offs have been outlined including among objectives, uncertainties, short- and long-term rewards, performance and learning (Runge and Bean 2020). To assist with navigating trade-offs among objectives, tools such as multi-criteria decision analysis, consequence tables (previously described in step four), cost–benefit analysis, and decision trees can help with comparison of alternatives (see Table 2; Gregory et al. 2012). Further, multi-criteria decision analysis can weigh objectives according to an individual stakeholder's values to estimate an overall value for each alternative, which could then be ranked by decision makers (Williams and Kendall 2017). There are tools available to elicit robust weights from stakeholders and/or decision makers for a set of objectives, as criteria may not be perceived equally (e.g., feasibility, cost, enthusiasm). This weighting of objectives can include swing weighting (von Winterfeldt and Edwards 1986), the rank-order centroid method (Edwards and Barron 1994; Goodwin and Wright 2009), and survey instruments that are sent to a broad group of stakeholders (see Robinson et al. 2016 for an example). Further, while there are many different ways to assign weights to criteria, the selection of weights can have serious implications on the decision-making process (Gregory et al. 2012). Additionally, direct discussion and agreement on a weighting scheme among stakeholders can be used (Robinson et al. 2021). The choice of tool can depend on the time available (e.g., surveys can take months), the group dynamics (e.g., willingness to hold open discussions, ability to understand more complicated methods like swing weighting), and the level of rigor needed. Martin et al. (2022) used multi-criteria decision analysis to assess the trade-offs between alternative wetland restoration locations in the Chesapeake Bay watershed to determine which location would best fit their objectives (for more information, please see Case Study #3). These tools can help measure the strength of trade-offs across objectives to identify which options are more or less acceptable. Agreements and discrepancies across stakeholders should be noted and considered during decision making.

Trade-offs are often present and it is important to balance them in order to maximize efficacy of ecological restoration (e.g., Regan et al. 2023). Indeed, Gann et al. (2019) have called for the use of decision-support tools (such as multi-criteria decision analysis) during ecological restoration to maximize long-term landscape sustainability for future generations under global climate change. To balance ecosystem services provided by ecological restoration, it is important to consider trade-offs specifically between ecological and social factors. For example, stakeholders could differ in terms of value for fish populations, where a trade-off could occur between conserving populations and supporting livelihoods and food security, each of which represent potential objectives to be identified and considered throughout the SDM process. Other trade-offs within ecological restoration can often stem from a general lack of human and financial resources (e.g., Meli et al. 2017). In a cost–benefit example, funding is limited but the objective of an ecological restoration project is to maximize the amount of land restored to conserve the population of an endangered species. Or in another example, it may be more cost-effective to implement passive restoration, but active restoration has been identified as the best performing alternative for ecological objectives.

3.6 Decide, implement, and monitor

Once the consequences and trade-offs have been considered and evaluated, the preferred alternative will be selected by decision makers and subsequently implemented. The decision may not achieve all objectives (i.e., a trade-off), but ideally the decision will support outcomes that are tolerable or satisficing (Hemming et al. 2022). Once a decision has been made, the details of logistics and planning for implementation can be developed with stakeholders (Runge et al. 2020). Although it is ideal to reduce or eliminate uncertainties, this is not always possible and sometimes the decision will have to be made in the face of uncertainties (Gregory et al. 2012). Uncertainties encountered within the SDM process may be resolved throughout implementation as new information is gathered through monitoring. Broadly, SDM promotes learning so that better decisions can be made in the future resulting in better outcomes and can also be incorporated into an iterative, adaptive management framework. Adaptive management is often considered as a special case of SDM for sequential decisions, either over time or space (Williams et al. 2007). The goal of adaptive management is to reduce uncertainty through experimental management actions, monitoring of outcomes, and updating of associated predictive models, in order to improve our decisions in the future (Walters 1986). Therefore, monitoring programs should be designed in a way that targets the most important uncertainties that act as the biggest barrier during decision making. Ideally, monitoring should have been initiated prior to implementation, as to set a baseline (i.e., "before") to compare the efficacy of the actions taken in terms of the objectives (Lyons et al. 2008). Monitoring contributes to further learning, so that when the cycle iteratively starts again, there are fewer uncertainties and a greater understanding.

Decisions and implementation often have to be made in the face of uncertainty within ecological restoration, as there are many unknowns in this new discipline. For example, the decision could include restoration techniques that have not been used before, so the outcome in terms of efficacy will be uncertain. The logistics and planning for the implementation of complex and long-term ecological restoration could be facilitated with project management and prioritization tools (Schwartz et al. 2018; Bower et al. 2018). These tools can track details of actions taken such as frequency, dates, people associated with each step, budget, and progress (Gregory et al. 2012). To advance the evidence base and decrease uncertainties regarding restoration ecology, it is crucial to conduct thorough monitoring. Too often ecological restoration is undertaken without any monitoring or lacks statistical rigor. As previously mentioned, starting monitoring before the implementation of ecological restoration will provide a baseline for comparisons to determine if the restoration was effective (Block et al. 2001). Further, if reference sites were used throughout the SDM process (e.g., as a goal), these sites could also be monitored as control sites. Taken together, monitoring before, after, and at control sites would provide enough information to undertake Before-After-Control-Impact assessments, which are very robust and are designed to detect environmental differences (Green 1979; Muller et al. 2016). Alternatively, tools such as multifunctionality indices, electronic tagging, and large-scale spatial monitoring regimes can be used for continued monitoring of restoration projects where applicable (Table 2). The same evaluation criteria that were decided upon in step two of the SDM framework should be used throughout monitoring. Monitoring is crucial in that it supports iteration through advances in understanding and refinements of techniques, particularly when implemented in an adaptive management framework (Conroy and Peterson 2006). Further, long-term monitoring is required as the timeline can span decades, for example, Gann et al. (2019) recommend at least a decade of monitoring after implementation.

4 Showcasing SDM and ecological restoration: case studies

Making decisions for ecological restoration can be particularly challenging when the factors are expansive or complex. To manage difficult decision making, SDM can be applied to help streamline the process and account for complexity. The case studies exemplify use of SDM for ecological restoration projects in instances where selection criteria were abstract and difficult to quantify, sensitive species were involved and threatened by management activities, and numerous collaborators with varying objectives and trade-offs were involved.

4.1 Ecosystem services and SDM

Historically, planning for restoration projects has been based primarily on environmental assessments and usually favors rural ecosystems that are considered more pristine than their urban or suburban counterparts (Martin et al. 2018). Here, Martin et al. (2018) argue that although restoration in urban areas is unlikely to achieve the full functioning of relatively more pristine ecosystems, urban restoration may provide more direct benefits in the context of ecosystem services. Using SDM alongside ecosystem services assessments to incorporate social and ecological benefits, Martin et al. (2018) worked alongside local stakeholders (i.e., a non-profit watershed council) to select restoration sites in the Woonasquatucket River watershed. The Woonasquatucket River watershed covers approximately 132 km^2 of mixed suburban and rural land in southern New England, USA and has been slowly degraded since the Industrial Revolution. This has largely impacted the river and attached wetlands, thereby degrading many of the ecosystem services provided. The stakeholders identified that the primary objectives should be to select restoration sites in the watershed that (1) maximized ecosystem benefits and (2) maximized social equity (i.e., urban versus rural areas). The group then identified 65 alternative restoration sites and actions (i.e., large-scale versus small-scale restoration) within the Woonasquatucket watershed that included both urban and rural locations based on previously identified areas of concern. They also selected five key ecosystem services (i.e., flood retention/risk reduction, scenic landscape/views, learning opportunities, recreation, birds/watching) that would be used in the later steps of the decision-making process.

To assess consequences, non-monetary benefit indicators were used to evaluate ecosystem services at each of the potential restoration sites, which allowed the group to compare smaller urban locations more adequately to larger, rural sites. Using this information along with 22 benefit indicators for ecosystem services and social equality and spatial analysis, Martin et al. (2018) assessed trade-offs using multi-criteria decision analysis (MCDA) to score and evaluate potential restoration sites. The results of this assessment identified multiple possible restoration sites across the alternative scenarios, although the authors do note that monitoring schemes for this work would be difficult to implement given the social component. Importantly, Martin et al. (2018) identified that by combining ecosystem services with SDM, environmental assessment bias that generally favors rural ecosystems can be accounted for, allowing urban ecosystems to be considered for restoration for their social benefits.

Incorporating both environmental and social impacts into restoration can be challenging as it presents more elements to base decision making on, which can leave managers and ecologists with an overwhelming number of factors to consider. This modernized framework for ecological restoration attempted to maximize the direct benefits of functioning ecosystems to more people (i.e., urban, suburban centers) while ensuring transparency through SDM. It offers a general outline of how ecosystem services as a proxy for social benefit can be fit into ecological restoration by working through an SDM framework, in the hopes of providing a context for planning in the future. Importantly, SDM is used here by the authors and stakeholders to make decision making transparent and documentable when many abstract components like ecosystem services are involved.

4.2 Species at-risk management and SDM

Restoration and management is particularly challenging when at-risk species are present. Doll et al. (2022) used SDM to help plan for ecological restoration following species invasion while balancing multiple competing objectives. More specifically, ecological restoration that was meant to increase the population of local species at-risk had the potential to do more harm to said species, prompting concerns from local stakeholders. Researchers looked to develop a plan for ecological restoration that would eliminate invasive plants while minimizing threats to the federally (United States) threatened Oregon silverspot butterfly (*Speyeria zerene hippolyta*). The Oregon silverspot is historically found in the coastal grasslands of California, Oregon, and Washington where they use early blue violet (*Viola adunca*) as host for their larval stage (Doll et al. 2022). Early blue violet is threatened by invasive plant species, thereby limiting the host abundance for the silverspots' larval stage (Doll et al. 2022). Several management tools have been used to address invasive species in butterfly habitat in the past including mechanical methods (i.e., manual removal), chemical methods (i.e., herbicides), livestock grazing, and burning (Dennehy et al. 2011; Huntzinger 2003; Moranz et al. 2014; Vogel et al. 2007). However, these techniquess were found to have direct negative impacts on butterflies and insects (Lázaro et al. 2016; Panzer 2002; Pereira et al. 2018; van Klink et al. 2020), which generated concern that the negative impact of management tools was outweighing the effect of the invasive species themselves. This presented land managers with challenging decisions to be made regarding how to manage a declining population without causing more harm. To help support land managers, Doll et al. (2022) SDM to help create a defensible, transparent, and robust decision for Oregon silverspot management.

The SDM process involved a diverse group of land managers, scientists, and decision analysts, who identified the main objectives to be (1) improving ecological conditions of coastal grasslands while maximizing (2) persistence and (3) distribution of the Oregon silverspot. The group also identified four other objectives, although objectives (2) and (3) were the primary focus of SDM. Following this, 16 management alternatives along with a no-treatment option were identified that included tools like grazing, burning, mowing, multiple possible herbicide options, and different combinations of these techniquess. Multiple herbicide options were selected as potential management tools, and this information was then used to model different life-history scenarios (i.e., population growth versus death). Models included both direct (negative) and indirect (positive) herbicide effects and allowed for a more in-depth analysis of trade-offs between different herbicide scenarios. The results indicated that three of the assessed herbicide strategies increased the population growth rate of the silverspot when compared to a no-treatment alternative. This information can now be used by the respective land managers to be implemented into Oregon silverspot habitat restoration.

Competing objectives such as invasive and at-risk species can make habitat restoration complicated for scientists and managers alike as seen here. This case study offers an outline of how SDM can be useful for analyzing multiple management options under different scenarios when the stakes are relatively high (i.e., species extinction). Restoration projects typically include many factors (management options, objectives, model scenarios) and the use of SDM allows more factors to be considered in final decisions, making management decisions ultimately more robust.

4.3 Action desirability and SDM

Restoration decisions are often complex and uncertain, especially when many people are involved. In modern ecological restoration, more voices are being included in project decision making such as restoration practitioners, project managers, scientists, strategy leads, and local and Indigenous communities (Matzek et al. 2014). The input of these stakeholders helps improve capacity to make meaningful change; however, with so much input, it can be difficult to make final decisions that are desirable to all parties. Further, limitations in human judgment and personal bias can impact the effectiveness of restoration decisions. This is particularly true when numerous objectives and trade-offs must be considered for a project and the outcome may result in actions that are not desirable to all. Martin et al. (2022) implemented SDM for a wetland restoration case study, in an attempt to evaluate the desirability (i.e., preference) of restoration options while minimizing complexity introduced by the inclusion of numerous stakeholders, objectives, and trade-offs.

Martin et al. (2022) worked alongside a diverse team consisting of members from the Nature Conservancy, U.S. Department of Agriculture Natural Resources Conservation Service, U.S. Fish and Wildlife Service, Maryland Department of Natural Resources, and Ducks Unlimited to assess wetland restoration potential in Chesapeake Bay in the United States. The Chesapeake Bay watershed covers 165,000 km^2 of land across seven jurisdictions (Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia, and District of Columbia), making large-scale collaboration an important part of restoration planning. Wetlands in these areas are largely threatened by water quality challenges—primarily eutrophication. The stakeholders collectively identified the main objectives for restoration to be (1) improving water quality in these threatened wetlands, and (2) increasing climate resilience. The stakeholders then identified seven sub-objectives and restoration alternatives based on the main two objectives along with spatial information relating to land use/cover. Trade-offs were assessed using multi-criteria decision analysis and principal component analysis to specifically determine which wetland locations within the Chesapeake Bay watershed would best fit the objectives. Further, the land use/cover data were used to visualize and prioritize restoration alternatives and trade-offs, so that the results of this analysis were shareable with local landowners to increase engagement in wetland restoration. The results produced multiple viable wetland restoration options across various locations. Three different regions appeared to be particularly promising in terms of restoration potential with respect to the above objectives and were strong options for landowner outreach as well, which the collaborating groups intended to implement immediately.

This case study exemplifies how SDM can be used when numerous opinions, objectives, and trade-offs must be considered in restoration planning. Martin et al. (2022) notes specifically that SDM in this case was advantageous for large-scale restoration decision making. The logical progression of SDM helps large decision-making groups work through problems more effectively while accounting for more factors and managing personal biases. This is particularly important as ecologists continue to work to include more relevant stakeholders in land management. Although SDM may not guarantee all important factors are included in an analysis, it helps to concentrate thinking on difficult aspects of a decision (i.e., multiple objectives/trade-offs, large-scale land cover) and reach more desirable outcomes for all involved.

5 Synthesis

Ecological restoration will continue to be essential in the Anthropocene and with biodiversity on the line, there remains urgency to "get it right" (Cooke et al. 2019). While ecological restoration is promising, there are many inherent challenges which could limit potential benefits. Limitations of ecological restoration can include balancing differences across stakeholders, limited budgets/capacities, complexities associated with working in the environment, or seemingly endless options during decision making. We posit that incorporating SDM into the ecological restoration process could result in better decision making and outcomes. Specifically, we synthesized how each of the six SDM steps could be applied to ecological restoration and provided examples of tools that could be used during the implementation process. Given that the United Nations has declared 2020–2030 the "Decade for Ecosystem Restoration," the state of global biodiversity requires urgent action and we argue that SDM could lead to more effective efforts.

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Declarations

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