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Management in Practice

Getting to a decision: using structured decision-making to gain consensus on approaches to invasive species control

Brett van Poorten[1,3,*] and Martina Beck[2]

[1]*British Columbia Ministry of Environment and Climate Change Strategy, 2202 Main Mall, Vancouver, BC, Canada*
[2]*British Columbia Ministry of Environment and Climate Change Strategy, 525 Superior Street, Victoria, BC, Canada*
[3]*Current Address: School of Resource and Environmental Management, Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada*

**Corresponding author*
E-mail: *bvanpoor@sfu.ca*

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Abstract

One of the great challenges with invasive alien species is deciding how to act when a new invasive population is detected. This is partly due to a variety of diverse perspectives on risk perception, objectives, predicted effectiveness of different management actions and uncertainty in likelihood of success for each action. These differences of opinion are largely due to divergent perspectives and experiences among individuals or agencies, and can be overcome with careful consideration, consensus-building and collective action. Structured decision-making (SDM) is a formal method to identify shared goals and facilitate discussion among diverse participants with an aim to collaboratively achieve an outcome in natural resource management. While SDM is used by many agencies to deal with a spectrum of natural resource decision problems, other agencies do not use this process. This article acts as a primer on SDM, discussing key considerations relevant to each step. We reinforce these steps by reporting on a case study using SDM. The problem we address is a non-native smallmouth bass (*Micropterus dolumieui* Lacépède, 1802) population discovered in Cultus Lake, British Columbia (BC), Canada, in 2018. Smallmouth bass are invasive to BC, and while they may provide a unique and satisfying experience for recreational fishers, they may also exert high predation rates on at-risk sockeye salmon *Oncorhynchus nerka* and coastrange sculpin *Cottus aleuticus* endemic to the lake. We report on early successes to this process and how it fostered collaboration and collective action to begin the process of population control for this invasive smallmouth bass population.

Key words: structured decision making, uncertainty, stakeholders, values, objectives

Introduction

Natural resource decisions are often complex and highly uncertain, there are fundamental trade-offs among competing objectives and each potential action has high risks and actions that are often irreversible (Maguire 2004). Trade-offs between objectives often reflect conflict between the desired goals of different agencies and stakeholders and can often represent different ecological, social and economic objectives of the system and stakeholders (Estevez et al. 2014). Individuals and groups have difficulty predicting complex outcomes and resolving trade-offs for a variety of reasons (Slovic et al. 1977; Schwenk 1984) and therefore are inherently poor at making these complex decisions unaided. Many resource managers with training in the natural sciences find working with and structuring feedback from groups difficult and uncomfortable, yet it is necessary in order to understand their values and solicit their input (Gregory et al. 2012). Overcoming many of these obstacles requires a structured approach that helps them navigate through a problem to provide decision advice (Arvai et al. 2001).

Many important decisions in aquatic management deal with whether, and how, to respond to invasive alien species. If unchecked, invasive alien species may lead to high ecological, economic and damage (Pejchar and Mooney 2009; Larson et al. 2011; Gallardo et al. 2015). However, many management actions involve high costs to implement (Buhle et al. 2005; Pimentel et al. 2005); if the wrong action is chosen, a decision-maker may face a situation of high ongoing costs of maintaining an inadequate control action until corrective action is taken, as well as high ecological, economic and social damage from a poorly-controlled invasive alien species. The choice of how to respond to an invasive alien species will be context-specific and should consider the biology of the invading population, physical characteristics of the receiving environment such as connectivity, prey and competitors in the receiving ecosystem and values being considered within control objectives. Response choice will also depend on a desired population outcome, between eradication, resulting from complete local extirpation of the population (Simberloff 2003), or ongoing maintenance of the population at a low level, often termed control. While rapid response is often best for achieving complete eradication or effective control, poorly considered decisions may lead to negative economic, ecological or social outcomes (e.g. Messing and Wright 2006).

The impacts of any invasive alien species or the actions taken to control them will rarely be experienced by the statutory decision maker: they are more often felt by one or more stakeholders (Shackleton et al. 2019). Public engagement is increasingly important for many management agencies (Shackleton et al. 2019), yet input from groups of stakeholders is often only gathered at one stage of the process, rather than including them as full participants in providing decision advice (Phillipson et al. 2012; Moon et al. 2015). For example, Arvai et al. (2001) reports a situation where feedback is used as the first stage of a decision process, followed by objective building and decision-making occurring away from the public. In fact, the efficacy of stakeholder engagement can be affected by a number of factors that should be carefully considered prior to initiating an engagement process (Reed et al. 2018; Shackleton et al. 2019). Stakeholders have key understandings of local conditions, expected or realized impacts and trade-offs (Moon et al. 2015); including stakeholders in the decision-making process can only help improve the outcome because their input reflects broad societal values (McDaniels et al. 1999; Gregory 2000; Novoa et al. 2018).

Unfortunately, gathering stakeholder input and effectively integrating it with an ecological understanding of the biology and impacts of an invasive population requires skills in facilitation, communication, and group deliberation (McDaniels et al. 1999; Gregory et al. 2001).

Decision analysis (DA) is a common tool in management science used to embrace uncertainty and provide advice on how to act given various uncertainties (model uncertainty, process uncertainty, observation uncertainty). DA is a step-by-step process that involves evaluating various management actions against objectives while admitting uncertainty in multiple states of nature (Robb and Peterman 1998; Gregory and Keeney 2002). This process has been used in a variety of contexts and helps clarify the processes involved in any decision. DA may include such decision tools as decision tables or decision trees (Keeney 1982); as such, it is not an alternative to these other tools, but explicitly includes them as a means to clarify alternatives and outcomes. However, DA does not provide guidance for how to create and compare objectives, how to determine the list of management actions or how to proceed once a decision is made, especially when working with a variety of interest groups. These important constructs within any decision usually influence the outcome of discussions and understandings among multiple agencies and individuals.

Structured decision-making (SDM) provides the framework for working with diverse groups of people to improve clarity, communication and even consensus around decisions (Gregory and Keeney 2002; Gregory et al. 2012). SDM often includes many or all of the components of DA and other decision analysis methods like Multi-Criteria Decision Making and Analytical Hierarchy Method (Kiker et al. 2005) but adds focus to initial steps of the decision by working with participants to understand the decision context and to formulate objectives and performance measures (Gregory et al. 2012). One of the strengths of SDM is it allows participation from stakeholders with divergent value systems, thereby leading to decision recommendations that reflect the broader society (Sharp et al. 2011; Estevez et al. 2014). SDM also goes beyond the decision itself by considering follow-up actions such as monitoring and adaptation as new data arrive. SDM requires value-based thinking to build objectives (McDaniels 2000; Arvai et al. 2001), as well as predicting outcomes and trade-offs, either quantitatively or qualitatively.

SDM is not new to natural resource management, though its use in addressing invasive alien species eradication or control decisions has been slow among some agencies in North America (Maguire 2004; Bogich and Shea 2008; Blomquist et al. 2010). The purpose of this paper is to provide a primer for the future facilitator or analyst in hopes of improving uptake of SDM as a valuable tool when decisions need to be made with respect to aquatic invasive alien species. We outline current practices used and apply it to a practical case study. Each step will be briefly discussed, emphasizing key considerations and pitfalls. We generally follow guidance laid out in Gregory et al. (2012) and show how these steps apply to a case study considering the management response to smallmouth bass (*Micropterus dolomieui* Lacépède, 1802) in a prominent sockeye salmon (*Oncorhynchus nerka* Walbaum, 1972) system. This case study is ongoing; our discussion is not about the outcomes found, but the process in getting to where we are. We use the case study as an example of how SDM works to engage multiple parties through the decision process at each step of SDM.

Case study: Cultus Lake smallmouth bass

Cultus Lake is a 635 ha lake in southwest British Columbia (BC), Canada, within the Fraser River watershed, approximately 150 km upstream from the Pacific Ocean. The lake is a popular recreation site, with permanent and seasonal homes and a provincial park surrounding much of the lake. The lake is also home to a well-studied and unique stock unit of sockeye salmon. Cultus Lake sockeye co-migrate in the Salish Sea and Fraser River with other highly abundant and commercially valuable sockeye stocks and therefore have declined over time due to overfishing as well as eutrophication of the lake environment. Cultus Lake is also home to an endemic population of coastrange sculpin (*Cottus aleuticus* Gilbert, 1896). Cultus sockeye salmon are listed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) as endangered (COSEWIC 2003); Cultus coastrange sculpin are listed as threatened (COSEWIC 2010). Cultus coastrange sculpin are also listed as endangered under the Canadian Species at Risk Act (Government of Canada 2003). The desire to recover economically valuable Cultus Lake sockeye salmon while not impacting other co-migrating sockeye stocks has led to prior application of both decision analysis and structured decision-making processes (Pestes et al. 2008; Gregory and Long 2009).

Anglers first discovered and reported smallmouth bass in Cultus Lake in 2018 (C. Schwindt, BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, *pers. comm.*). Smallmouth bass are not native to western North America and are often seen as a threat to native biodiversity due to high predation mortality imposed on valuable salmon stocks in invaded watersheds (Tabor et al. 1993, 2007). Smallmouth bass are popular recreationally and thought to have been transferred to the lake illegally, since there are no other known smallmouth bass populations within the lower Fraser River basin. The presence of smallmouth bass in Cultus Lake is viewed as a threat to Cultus Lake sockeye and Cultus Lake coastrange sculpin; early sampling has found sockeye and an undetermined species of sculpin in smallmouth bass stomachs (B. Heise, Thompson Rivers University, *pers. comm.*).

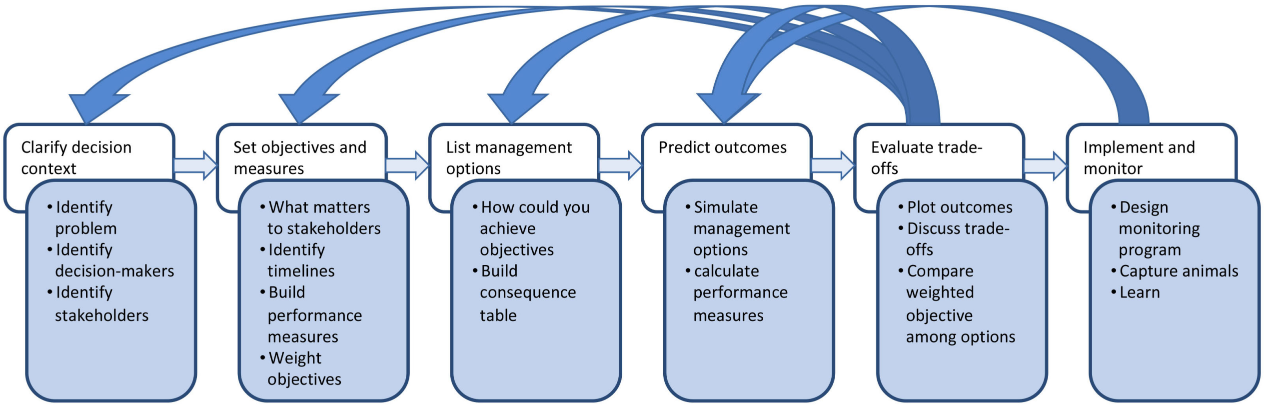

Figure 1. Steps involved in structured decision-making. Steps can be re-evaluated at any point; responses should be re-evaluated once new data is gathered following implementation. Adapted from Liu and Cook (2016).

Steps in structured decision-making

Structured decision-making has multiple stages but is not necessarily a linear process; each step can be revisited at any time. SDM is essentially a means to operationalize decision analysis; therefore, the steps described here are similar to those used for that process (Robb and Peterman 1998). The process of SDM will likely vary across practitioners; we closely follow the process and guidance described in Gregory et al. (2012). Steps in SDM can include (Figure 1; Gregory et al. 2012): (1) clarifying the decision context; (2) determining objectives and performance measures of those objectives; (3) listing management actions; (4) predict outcomes; (5) evaluating trade-offs among objectives; and (6) implementing a decision and monitor outcomes. These steps may be prescriptive, as suggested by the light blue arrows in Figure 1, or may serve as a general guideline through the process. Each decision will be different: practitioners should not feel compelled to go in order at the expense of progress or creativity.

Though any steps may be revisited at any time, the diagram in Figure 1 shows two key stages where it makes sense to reflect on past steps, based on the dark arrows: evaluating trade-offs and implement and monitor. Once trade-offs are evaluated and described, stakeholders may ask to revisit earlier steps. This may be to add additional objectives, or may be to consider additional actions. This is completely normal and reinforces the informal nature of decisions. The second point for reflection is following implementation (Figure 1). Once the decision is implemented and monitored, new data may provide a means to improve model parameters, re-evaluate outcomes and determine if the chosen course of action is indeed the correct path. This demonstrates a link to adaptive management (Walters 1986; Williams 2011) as a means of better understanding uncertain processes.

Clarify the decision context

The decision context starts with stating the problem at hand as a decision to be made. The decision may be a single decision, or a series of nested decisions. However, the context also involves deciding who the ultimate decision-maker(s) are (Gregory et al. 2012). Once the decision has been framed, it is important to determine organizational aspects of the decision such as determining what experts to consult with, the agencies that may need to be included, and the analyst(s) that should be used to predict future conditions (this may be the facilitator as well).

A critical organizational aspect is determining who the important stakeholders will be (Novoa et al. 2018). We use the term stakeholder in the broadest possible sense, including government agencies, affected First Nations, local interest groups, land owners, industry, and so on (Bryson 2004). Listing people and organizations impacted or potentially upset by a decision will help determine who should be involved in decision-making discussions (Reed et al. 2009). This includes stakeholders who may derive value from the invasive species and therefore may initially resist control efforts (Larson et al. 2011). Stakeholder values are a key component of the decision process because they help identify what matters to them as stakeholders, which leads to determining objectives based on values from all groups represented (Gregory 2000; McDaniels 2000). The group of invited stakeholders should be considered carefully: inviting too broad a group will slow the process and be harder to structure their input (Gregory and Keeney 2002); too narrow a group will ignore important voices and may lead to resentment later by those not included (Bryson 2004).

For the Cultus Lake case study, relevant stakeholders included biologists and scientists from the Provincial and Federal governments, academics with experience in invasive alien species, local angler groups and representatives from the Soowahlie First Nation, whose traditional territory includes the lake and watershed. Other recreational users of the lake, such as hikers, campers and boaters were excluded from the process because we determined they were not directly affected by the presence or impacts of smallmouth bass. While they may inadvertently transfer other invasive alien species, that would not be relevant to a decision regarding the smallmouth bass invasion specifically. Determining who may be a stakeholder is based on knowledge of the area and people. We were fortunate that several participants live and work in the community, so have an honest census of community groups; if that were not the case, it would be necessary to do appropriate research to understand who relevant stakeholder groups are, to avoid introducing bias in who should be considered and why. The outcome of the process will be influenced by who is included in the process, so this step is very important.

A preliminary scoping meeting was held April 25, 2019 including only Provincial (n = 4) and Federal (n = 2) government biologists and scientists and an university professor with an invasive species specialization (n = 1); a second meeting held on August 20, 2019, was opened to representatives from all stakeholder groups. This meeting included five Provincial government biologists and scientists, two Federal government biologists, the university professor and three representatives from a lake stewardship club. Representatives from the Soowahlie First Nation were invited but unavailable at the last minute, but have been kept up to date and continue to be part of the ongoing discussion and will be fully involved in later meetings. The absence of an important participant was an unexpected issue for the Cultus Lake process and one that likely influenced the outcome of the process. Re-engaging the Soowahlie First Nation is an ongoing challenge, which the entire group is working to address.

Meetings loosely followed an agenda, which was meant to ensure all relevant topics were discussed. The agenda essentially included the first four steps of structured decision-making, but within each agenda item, discussion was organic to promote collaboration, dialogue and creativity. The first author facilitated each meeting by guiding participants through the agenda, taking care not to hamper discussion. Meetings started by discussing the personal relationship participants have with Cultus Lake and the aquatic community. Some participants fish the lake with their children, others live in the area. First Nations use and values were discussed based on the understanding of participants, although actual First Nations community members regrettably were not present to contribute to this discussion. Other topics included the aquatic community as well as social and community groups, fishing events and other seasonal events related to the lake. Finally, discussions led to likely timing of bass introduction into the lake, threats and reasonable outcomes if the population persists. All these conversations help provide background, which not only helps each participant relax and find common values with others, but also leads into the decision context for the problem. The decision context at Cultus Lake included determining whom the statutory decision maker was, which community groups existed and verifying which groups should be included in SDM discussions.

Determine objectives

Conflict among interest groups often occurs because of differences in values among stakeholders and poorly defined objectives (Hilborn 2007; Estevez et al. 2014). Objectives reflect aspects of the system that are important in a decision (Liu and Cook 2016): what are the things that could be improved or reduced through this decision, relative to the status quo. This is a value-based question for which stakeholder input is essential (Gregory 2000). There may be times when stakeholder values contradict government policies; these policies can be seen as constraints which stakeholders must move within, rather than being a source of difficulty. Discussion with stakeholders around what matters at the end of the invasive alien species management process will help inform and build objectives (Liu and Cook 2016).

Table 1. Definition of important terms in decision-making.

Term	Definition
Objective	A desired state or goal of the system
Fundamental objectives	An objective related to the overall end-state desired
Means objectives	An objective necessary to move the system closer to the fundamental objective
Multi-attribute objective	A weighted aggregation of individual objectives for different attributes of a system
Decision	A conclusion of which action to take
Performance measure	A quantitative or qualitative measure of the current state of the system with respect to a particular objective
Eradication	Complete removal of a species or population
Control	Ongoing suppression of a species or population
Tactic	An action taken to achieve one or more objectives
Trade-off	A balance to be achieved between multiple desired, but incompatible objectives
Model	A simplified representation of reality, used as a means of predicting outcomes of different tactics

Each objective must be evaluated by some performance measure of the system state, which is used to reflect and compare the predicted performance of each management action (Gregory et al. 2012). Performance measures can be difficult to construct, depending on the objectives determined. Gregory et al. (2012) describes three types of measures. The first is natural performance measures, which are direct, quantitative measures of the system. For example, if the objective were low ongoing control costs, dollars spent each year would be a natural measure. Natural measures are preferred because they are unambiguous and interpretable. However, natural measures are difficult because objectives are either intangible (e.g. "sustainable use") or because data to obtain these measures are difficult to attain and/or uncertain (e.g. fish abundance: Gregory et al. 2012). The second measure is a proxy: something thought to be correlated with objectives, which might be difficult to measure directly (catch rate is a common proxy for total abundance). The final type of measure is a constructed measure, often an artificial scale used to describe the outcome. For example, a questionnaire might be used to have each member rank a variety of outcomes from one to ten (e.g. outcome A returned a 2; outcome B returned a 7). These can then be interpolated to construct a non-linear measure among outcome possibilities. When using constructed measures, it is important to carefully describe what each level means to participants and decision-makers (Gregory et al. 2012).

Once objectives and their measures have been determined, it is necessary to think about how to evaluate and communicate outcomes. Some suggest combining performance measures into a single multi-attribute performance measure (Table 1; Kiker et al. 2005), where all performance measures are weighted in a way that reflects their importance to the final decision. This may require re-scaling all measures so they are comparable; each objective could then be weighted on a scale from one to ten and final objectives averaged across participants (e.g. Liu and Cook 2016). Doing so provides a mean reflection of how each management action is predicted to perform. However, because the multi-attribute measure is a combination of multiple measures, each weighted against one another, the absolute value is meaningless to participants, leading to difficulties in interpretation (Irwin et al. 2011). Note that averaging across participants is often inappropriate because there is disagreement among participants in how different objectives should be weighted. This provides an opportunity for discussion regarding views and opinions among participants to see where agreement and disagreement comes from. If a resolution cannot be reached, the weighting of each participant may be evaluated separately so that each outcome is presented as an outcome to discuss trade-offs among participants. Understanding where these disagreements arise and respecting these different values and backgrounds is an important outcome of the process and can help improve acceptance of the final decision (Estevez et al. 2014; Reed et al. 2018; Shackleton et al. 2019).

The other option in communicating outcomes is to simply report performance measures and show how they trade off against one another. Visualizing trade-offs becomes key with this option. This option does not require an explicit weighting of objectives, which is useful in avoiding confrontation among participants, but instead moves it to a later stage (Evaluate Trade-off stage, below). The disadvantage of this method is it may lead to a more ambiguous decision, as weightings may not be formally defined and recorded. SDM practitioners should think carefully about how to approach and communicate trade-offs when determining whether to create a single, weighted utility measure or whether to provide direct measures of each objective. Recognizing the advantages and limitations of the two approaches, both were presented to decision-makers in the Cultus Lake case study to enable them to make an informed decision based on the approach that was suitable to them.

Participants in the Cultus Lake case study were asked the timeframe they want to consider for management and what they wanted to achieve in that time. The facilitator then used this to suggest objectives for management. As with nearly all invasive species problems, a primary question was whether eradication or control were important objectives (see definitions in Table 1). Both can be important to different participants for different reasons (Liu et al. 2012). It is important that participants clearly understand the difference between these two terms so they can appropriately judge effort, cost, timelines and outcomes of these two objectives. All participants suggested objectives in an open dialogue. Each objective was discussed and determined to be either a fundamental or means objectives: fundamental objectives are the results of interest to decision-makers; means objectives relate to actions that lead to achieving fundamental objectives (Table 1; Lyons et al. 2008; Liu and Cook 2016). This is an important distinction and helps participants understand the broader perspective of the decision to be made. Finally, participants were asked how they would know whether their objectives were met. All participants used this discussion to develop mutually agreed-upon performance measures. All objectives and performance measures are listed in Table 2.

Table 2. Means and ends objectives and performance measures for smallmouth bass management in Cultus Lake BC. Weights reflect the importance participants in SDM placed on each objective. Bolded weights are for ends objectives; unbolded weights are for means objectives.

Ends objective	Means objective	Performance Measure	Importance weight	
Low final abundance				**0.42**
	Extirpation	Probability of extirpation	0.17	
	Few nests observed	Nests	0.25	
Public participation				**0.32**
	Volunteer anglers	Number of angler-days	0.18	
	Volunteers search for nests	Number of days searching	0.14	
Non-target impacts				**0.26**
	Avoid capture of species at risk of extirpation	Number of gears likely to target at-risk species	0.18	
	Avoid capture of species not at risk of extirpation	Number of gears likely to target other species	0.08	

Cultus Lake workshop participants immediately recognized extirpation of smallmouth bass as an objective but did not weight it highly because there was little hope that it could be achieved and because of the likely harm to species at risk of extirpation if more effective, but less selective methods were used (e.g. piscicide). Control was more highly weighted, with a performance measure based on the number of bass nests seen per year during annual surveys. Public participation and public education were highly valued by managers and stakeholders, who indicated a desire to include anglers in annual removal efforts, nest sighting and destruction, as well as informing the public of activities through signs and presence at public events. Finally, minimizing ecosystem impact of control (e.g. bycatch) was also an important outcome.

Each objective was expressed on a scale of 0–1. The extirpation objective value was calculated (using the model described in the Predict Outcomes step) as the proportion of stochastic model evaluations resulting in extirpation. The objective related to number of nests was calculated as a function of stochastic model runs resulting in fewer than 100 nests. For these runs, a utility was calculated as the sum of 1.0 minus the number of nests/100. Model runs resulting in greater than 100 nests were scored with a zero for this objective. This value was divided by the total number of model evaluations, to give a final objective value. The objective values related to use of volunteers for angling or nest searching was given a 1.0 if the action evaluated included volunteer anglers or nest searching, respectively, and a zero otherwise. The objective functions related to avoiding capture risk for at-risk and not-at-risk was calculated as 1.0 minus the proportion of fish in each category residing in the lake predicted to be captured using each gear used in each management action. For example, if gill nets were used in an action, they would be predicted to capture one of the two species at risk of extirpation (coastrange sculpin) resulting in an objective value of 1.0 − 0.5 = 0.5; and they would capture five of the 30 not at-risk species, resulting in an objective value of 1.0 − 0.167 = 0.833.

Participants then weighted fundamental objectives for later construction of a multi-attribute objective function. We chose to ask participants to allocate an arbitrary 100 points (where each point is an "importance score") among fundamental objectives. This process forces participants to make trade-offs among objectives. Participants also weighted means objectives by allocating points given to each fundamental objective among means objectives related to it (see Table 2). After each participant had weighted objectives, weights for each fundamental and means objective were averaged across participants. This decision of how to combine weighting was agreed to by all participants.

List management actions

Prior to listing management actions, it is important for all participants to be equally educated about the invasive alien species considered, the receiving community and expected interactions between the two. This may require a short tutorial on species biology, behaviour, seasonality of spawning, shifts in diet preference throughout the year, habitat use and growth rate. This overview will help everyone start thinking of ways to disrupt the species life cycle and make impacts on population abundance and impact.

Imagining management actions is often the part of the process where participants are most engaged and animated, partly because it can be very creative and partly because different groups may start thinking of how they can participate in ongoing management. A list of management actions may include extreme (poisons, explosives), targeted (manual removal), or socially minded capture actions (use of volunteers). Every option should be recorded and acknowledged, no matter how impractical or unlikely. Some management actions may drop out later in the process, but allowing all participants equal opportunity to contribute is an important outcome of the process.

Management actions may also include different levels of intensity of the same capture gear. For example, one action may be to use five panels of gill net per night for ten nights, another to use 20 panels of net per night for ten nights. This highlights the importance of specificity: it is necessary for participants to state clearly what a unit of removal effort will be. In other words, how many net-nights or angler-hours should be considered as a baseline? Stakeholders who do not normally fish or handle capture gear may need some time to understand these concepts, but these definitions will be important when parameterizing the model, particularly when thinking about capture efficiency of one management action over another. Moreover, they remove any linguistic uncertainty in discussions (Latombe et al. 2019), so all participants are describing the same action.

At this point, pause and re-evaluate everything the group has accomplished. This may sometimes be achieved by constructing a simple response table (see Table 3), also referred to as a consequence table among practitioners (Gregory et al. 2012). A response table lists all management

Table 3. Simple response table used to quickly determine high, medium, low, or zero probability of achieving each sub-objective. This may be formed by consensus or filled out individually by participants.

	Sub-objectives					
Management tactic	Extirpation	Few nests observed	Volunteer anglers	Volunteer nest searchers	Avoid capture of species at risk of extirpation	Avoid capture of species not at risk of extirpation
Do nothing	Low	Low	Zero	Zero	High	High
Destroy nest with eggs	Medium	Medium	Zero	Zero	High	High
Destroy nest with larvae	Medium	Medium	Zero	Zero	High	High
Target adults on nest	Medium	Medium	Zero	Zero	Medium	Medium
Short set gill net	Low	Low	Zero	Zero	Low	Low
Angling	Low	Low	Zero	Zero	High	Medium
Destroy nests with eggs and larvae; target adults on nests	Medium	Medium	Zero	Zero	Medium	Medium
Destroy nests with eggs and larvae; target adults on nests; angling	Medium	Medium	Zero	Zero	Medium	Medium
Destroy nests with eggs and larvae; target adults on nests; short set gill net	Medium	Medium	Zero	Zero	Low	Low
Destroy nests with eggs and larvae; target adults on nests; short set gill net; angling	Medium	Medium	Zero	Zero	Low	Low
Volunteers to destroy nests with eggs and larvae; target adults on nest	High	High	High	High	Medium	Medium
Volunteers to destroy nests with eggs and larvae; target adults on nest; angling	High	High	High	High	Low	Medium
Volunteers to destroy nests with eggs and larvae; target adults on nest; short set gill net	High	High	High	High	Low	Low
Volunteers to destroy nests with eggs and larvae; target adults on nest; short set gill net; angling	High	High	High	High	Low	Low
Destroy nests with eggs and larvae	Low	Medium	Zero	Zero	High	High
Short set gill net; angling	Low	Low	Zero	Zero	Low	Low
Volunteers to destroy nests with eggs and larvae	High	High	High	High	High	High
Destroy nests with eggs and larvae; angling	Low	Medium	High	High	High	Medium
Volunteers to destroy nests with eggs and larvae; angling	High	High	High	High	High	Medium
Target adults on nests; short set gill net	Low	Medium	Zero	Zero	Low	Low

actions as rows and objectives as columns. The facilitator then goes through each objective – management action combination and asks how the action might be expected to impact each objective (Table 3). Because there is no quantitative model involved yet, this is an informal check-in to see how useful each management action will be in achieving each objective. For each objective – action combination, indicate the relative expected impact of each management action on each objective or whether there is no expected impact. Each participant can do this independently and the group can then discuss all outcomes at each position on the table to see if there is agreement. Although these outcomes are the result of the "mental model" of all participants, there are likely similarities in predicted outcomes among participants. Any differences will be useful points of discussion among participants to help understand different points of view.

Once the simple response table is complete, examine the outcome. If there are management actions that have no impact on any objective or objectives that are not affected by any management actions, these can likely be removed from further consideration. Even if it is important to some groups, an objective that is not impacted by any action is not part of this decision (Gregory et al. 2012). Alternately, this may present an opportunity to think of additional management actions that will directly impact this objective. This process will likely reduce the list of objectives and may remove at least some management actions, thereby streamlining further work. In fact, in some cases, the best solution may become apparent, in which case it may be best to stop and make a decision rather than spending time on a quantitative analysis (Gregory and Keeney 2002).

In the Cultus Lake workshops, participants discussed smallmouth bass biology, including timing of staging, spawning and guarding, nest fidelity, spatial ontogeny and habitat use, as well as habitat overlaps and interactions with other species in the lake. Discussion then switched to management actions, which reflected findings from the discussion of smallmouth bass biology. Smallmouth bass males construct and guard nests in the spring, so specifically finding and destroying nests were important considerations for management (Loppnow et al. 2013). Other management actions were less selective (such as using gill nets) and were likely to impact other species. All actions were considered, and combinations of actions were extensively listed to get a full picture of every response possible.

The Cultus Lake workshops resulted in five individual removal actions, which were combined in various ways to produce 20 management actions. Evaluating controls and objectives in a simple response table led to the removal of “public awareness” from the final list of objectives. All participants realized that educating the public on what we were doing and why is an important objective and dedicated ourselves to including public education in everything we did. However educating the public was never an explicit management action discussed; that is, it was implicit in every management action. Therefore it could not be influenced by any management action being considered, so it was not relevant to the decision on how to respond to smallmouth bass.

Participants were then asked to help provide parameters that describe the Cultus Lake smallmouth bass population. This included population-specific information such as perceived current abundance, expected equilibrium abundance if left uncontrolled, and general parameters for smallmouth bass such as individual growth rate information, natural mortality, strength of density dependence in survival and fecundity. Participants were also asked to provide expected catch rates with each capture gear, which can later be used to calculate capture probability per unit effort (also referred to as catchability). Likewise, participants were asked whether and how capture efficiency varies with body size or life stage, which led to a discussion regarding relative selection of bass in different gears as they grow.

Participants were also asked about technical details of each management action that relate to objectives and performance measures. For Cultus Lake smallmouth bass, this focused on expected up-front and annual costs. Many participants, especially government biologists, had a general idea of these values, or could quickly obtain them following the workshop. Having participants provide this information provides additional ownership and pride in the result and promoted uptake of the decision proposed by the process (Phillipson et al. 2012).

Much of this work had already been completed through literature review, but it was important to run through implications of different parameters with participants to give them the opportunity to discuss and disagree with parameters. It was also important to communicate that these parameters are not necessarily correct, but best guesses to help steer the approach to the problem. As the final decision is implemented and captures and population status are monitored, parameters will be updated with data from ongoing removals.

When the discussion turned to defining parameters, gear efficiency and other technical details, there was a noticeable divide among participants. Agency biologists and those familiar with fish capture were very eager to engage in this process, while participants from outside organizations were visibly bored, or left for the day. Based on the Cultus Lake experience, it seems that this component of the process is best left to willing participants, or removed from the process entirely and done outside the workshop process.

Predict outcomes

Estimating outcomes of each management action is usually the most technical part of the process, often involving quantitative models used to predict how each management action may impact the system and how this relates to performance measures. Models should be as simple as possible to avoid complications, which will either lead to unseen "bugs" in the model or poor understanding of the model by stakeholders. Assumptions should be explicitly stated to further help participants understand limitations and lead to further discussion, which will help increase understanding of the model. Key components include an ability to realistically model target species removals using each stated management method and provide performance measures as described by participants. Models should be built that are tailored to the system unless each management action and performance is sufficiently common to be included in a pre-programmed model. In the Cultus Lake example, the program $INVAS_{PVA}$ (van Poorten et al. 2019) was used to evaluate scenarios. This model was chosen because it was able to handle all management actions listed by participants and all performance measures could be calculated from model output. This is a stochastic model, allowing extirpation probability to be calculated as the proportion of simulated models that go extinct within a certain time frame. While some parameters are uncertain, such as carrying capacity, others are fixed (van Poorten et al. 2019). We also conducted each simulation across several starting values and reported the expected value of the multi-attribute utility across all starting values. The model calculated the outcome of each management action on the smallmouth bass population over a 25-year timeframe. For each management action, performance measures identified by workshop participants were calculated based on model outputs.

Evaluate trade-offs

Nearly any decision will involve multiple objectives which are most likely not complementary. Trade-offs in these decisions must be acknowledged and evaluated. While weighting of various objectives and measures may be accomplished by participants already, it is important to still recognize how any single decision will affect each objective and value considered by participants. This step almost certainly occurs after initial meetings because they require outcomes to be predicted from a model.

To understand trade-offs, it is useful to show how different decisions are predicted to affect different performance measures, as calculated from model outcomes. Bar plots can be useful for evaluating how each management action affects performance measures related to single objectives (Figure 2). These plots demonstrate how each action affect a specific fundamental objective. In Figure 2, the calculated measure of avoiding species in Cultus Lake that are at risk of extirpation and those not at risk of extirpation are shown for each management action. This helps participants and decision makers see that some actions, such as destroying eggs with nests or larvae, have low risk to other species, whereas other actions, such as gill nets, are more general and present a real threat to these coexisting species. These plots will open discussion or consideration among participants and decision-makers. This may lead to reconsidering actions (either how much effort to put into any one action or additional actions that have not been considered yet). Revisiting previous steps is encouraged in order to get to the best possible outcome given the objectives among participants (Figure 1).

If a multi-attribute objective measure has been developed using weighed objectives (Table 2), demonstrate how this measure varies across all possible actions (Figure 3). This will help users understand how various actions relate to their overall objective. Is there only one that stands out among all others? Are there several actions that are quite similar? In the latter case, this may lead to more discussion and examination of trade-offs

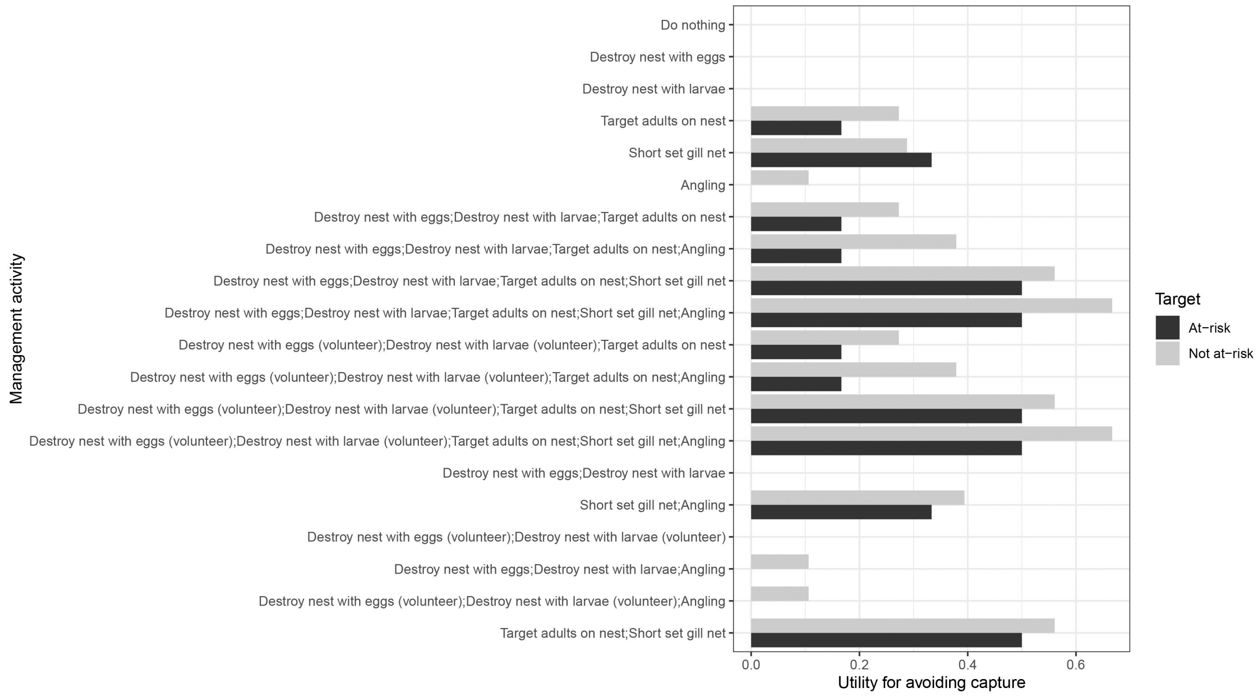

Figure 2. Calculated utility of avoiding fish species at-risk and not at-risk of extirpation in Cultus Lake, BC, across all combinations of smallmouth bass control. Utility is presented on a scale from 0–1.

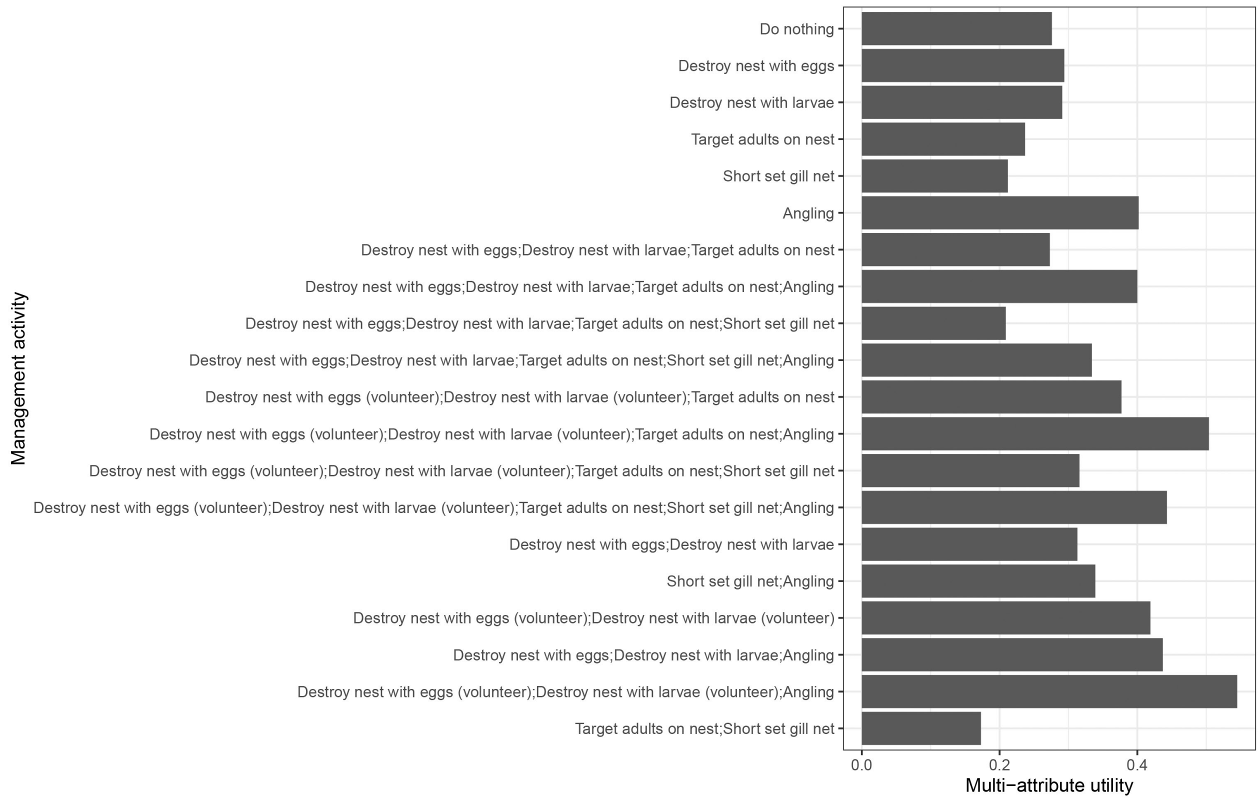

Figure 3. Total multi-attribute utility including all weighted objectives for responding to smallmouth bass in Cultus Lake, BC, across all management activities. Each utility was on a scale from 0-1, so the multi-attribute scale also ranges from 0–1.

that are being made; two actions may score similarly because they address different objectives. The absolute objective value calculated for any single action should not be the focus of conversation at this point, because they are not relevant for the specific decision being considered. Keep participants focused on the decision being considered: how to respond to an invasive alien species. The objective values for each action relative to one another will help address that decision.

Finally, it is important to conduct sensitivity analyses to demonstrate how resilient your decision is to parameter uncertainty. One option is elasticity, calculated as the mean proportional change in the performance measure divided by a given proportional change (often 10%) in the parameter (Buhle et al. 2005). This will provide an indication of which performance measures are most sensitive and help you understand which parameters are most important to accurately represent or measure. Another measure of sensitivity will be to see how uncertainty in different parameters lead to a change in the suggested optimal decisions (Peterman and Anderson 1999; Gregory et al. 2012; van Poorten et al. 2019).

Performance measures for each management action on Cultus Lake smallmouth bass were plotted and reported back to participants (Figures 2, 3) once outcomes were predicted following the workshops. This led to a discussion on trade-offs and implementation. This will also be used in a further workshop with Soowahlie First Nation representatives, so they may build their own objectives and control measures. To date, we have not completed the process because we have not started implementation or monitoring, but the process has already shown benefits. The SDM workshops have led to mutual understanding of the problem, which leads to further communication as participants go back to their constituents and inform them of the issue and the planned response. Participants have used outcomes from the process to apply for funds to carry out management, which demonstrates commitment to the results. Initial data collection in a pilot year also helped improve some parameters. Planning management action for the first year is currently underway.

Implement and monitor

Once the group has decided the action to take, it is important to think about how to learn from the system through time. Think about the parameters that went into the model: are there ways to monitor the population that will help improve precision of various parameters? If abundance can be estimated using some method (removal or mark recapture methods), catch rates from removals can be used to calculate capture probability of each sampling gear used. These factors should be considered long before setting the first trap or casting the first line. Especially consider the outcome of sensitivity analyses: if decisions are especially sensitive to one or more parameter, consider how to monitor the invasive alien population, or conduct experiments outside the main management effort, to improve estimates for those parameters. Considering data collection and eventual incorporation back into an analytical model should be the first step of any management plan.

As the population is monitored over time, information gathered may indicate that the chosen management method(s) are not as efficient as initially thought. There may be conditions at the invaded habitat which make some capture methods less efficient than expected. Confronting models with data at the end of each sampling season is an important part of the decision process. It may be that new data results in a different decision on how best to manage the population given objectives determined early in the process. It is important to not be beholden to earlier decisions. If a change in approach is warranted given data collected, so be it (Gregory and Keeney 2002). This is often referred to as passive adaptive management, where learning and reducing uncertainty occurs as an outcome of a management decision (Walters 1986; Williams 2011). If a change in management approach is necessary later in the process, it will be straightforward to rationalize to decision-makers and the public because the steps of SDM have been documented, though note that careful work and understanding among all stakeholders will be necessary to avoid renewed conflict (Ratner et al. 2018).

Extensions to SDM

Decision analysis and structured decision-making are meant to rank actions based on stated objectives despite uncertainty in outcomes (Peterman and Anderson 1999). However, uncertainty in some parameters can lead to several decisions with nearly the same predicted outcomes, as revealed through sensitivity analysis (Peterman and Anderson 1999). As a result of the SDM process, it may be desirable to conduct further analysis, experiments or monitoring to reduce uncertainty in one or more processes. There are several ways to proceed.

The first extension is to evaluate the value of information, which reveals whether the effort to resolve parameter uncertainty will make any difference to the outcome of a decision. This can be conducted through an Expected Value of Perfect Information analysis (EVPI; Walters 1986; Runge et al. 2011) in which you evaluate how calculated utility would improve over the current predicted utility achieved under the chosen management action if you knew one or more parameters perfectly (Moore and Runge 2012). This reveals how much could be gained by spending time and money conducting further targeted monitoring to more accurately understand the parameter of interest and how the chosen decision might change if that parameter were known. It is important to recognize that value in this sense does not need to refer to monetary value, but value with respect to the objectives of the decision (Runge et al. 2011). This is an upper threshold: no amount of monitoring will result in a perfectly precise estimate of a parameter. Therefore, the other analytical option will be the Expected Value of Imperfect Information (EVII) where the experiment or monitoring needed to improve understanding of one or more parameters is simulated and those parameters of interest are estimated by statistically fitting to the simulated data. Simulated management of the invasive population, and associated performance measures, continues as parameter estimates improve. If cost is one of the performance measures of the process, VOII will result in a relatively accurate trade-off between acting now and waiting until more information is available before acting.

The second extension to SDM is active adaptive management (Williams 2011), in which two or more management actions are conducted simultaneously (across multiple invaded habitats) or in tandem over time (if only one habitat is invaded) with replication where possible (Walters 1986). This process can take a long time and require extensive resources. While the benefits of large-scale "learning while doing" experiments may include improved understanding of population response to different management actions understanding of institutional barriers and learning from unexpected outcomes (Walters 1986; Hugues et al. 2007), there are now many cautionary tales and retrospectives that warn of the difficulties in establishing and maintaining such a program (Lee 1999; Walters 2007; Pine et al. 2009).

Discussion

Structured decision-making provides a systematic formula for providing decision advice based on the input and experience of a group of individuals. Many managers are trained as biologists with limited experience of communications, social sciences or human dimensions (Barber and Taylor 1990; Jacobson and McDuff 1998); therefore, interacting with, and facilitating discussions among stakeholders does not always come naturally. SDM overcomes many of the cognitive shortcuts taken by individuals and groups in such situations (Tversky and Kahneman 1974; Slovic et al. 1977). In doing so, it is seen as a key tool in providing robust decisions (Gregory et al. 2012).

Structured decision-making provides benefits far beyond helping get to a decision. First, it provides a forum for other agencies and stakeholders to be a part of the decision process. There is an emphasis among management agencies on including public input, but this is often achieved through polls, unstructured town hall meetings and advisory committees (Shackleton et al. 2019). While these venues provide an opportunity for the public to provide constructive criticism and suggestions, they do not see how their suggestions are used to improve decisions (Phillipson et al. 2012). Integrating stakeholder values is important in setting objectives and examining trade-offs among different stakeholder opinions; in short, the parts of a decision that can cause dissatisfaction among groups because they don't see, understand or agree with the ways objectives are traded-off. By involving stakeholders in building objectives and suggesting management actions, there is an opportunity to educate the public about the values considered by management and where the values of each stakeholder sit within that context (Arvai et al. 2001; Shackleton et al. 2019).

The second benefit of SDM is in communication. Each step outlined above should be carefully documented and then communicated back to stakeholders (Gregory et al. 2012). This serves several goals. Documenting the decision process helps in later iterations when decisions are revisited or the process is revised in the face of new data (Gregory and Keeney 2002; Gregory et al. 2012). A fully documented process also helps open the decision criteria and objectives to public discussion, so any decision is put in the proper context.

There were several lessons learned from the Cultus Lake case study. Perhaps most important was the importance of engaging all stakeholders throughout the process where possible. The Soowahlie First Nation was interested in participating in the process, but a last-minute issue called the participant away. Every effort has been made to hold a workshop with them, but other priorities, combined with small staff, have made that impossible so far. This is unfortunate, because their perspective and history on the land is invaluable in a process like this; excluding some stakeholder groups could certainly lead to bias in outcomes of any SDM process (Reed et al. 2009). Another issue raised has been the possibility of disagreement among stakeholders. We were fortunate that all stakeholders had the same general outcomes in mind. Situations where objectives or weighting of objectives leads to wildly different outcomes would be much more difficult to address and communicate. Facilitators should take the time to respect and explore these differences, rather than trying to average across them. Incorporating these broad viewpoints is what drives the need for stakeholder engagement in the first place (Sharp et al. 2011; Estevez et al. 2014). Finally, this process requires skilled communicators (Gregory et al. 2012). Engaging in structured decision-making for the first time is daunting and errors occur. Leading people through the process may be difficult; communicating outcomes and trade-offs is equally difficult. Prior experience or consideration in science communication and stakeholder engagement will go a long way to improving the process for all involved.

Unfortunately, there are few one-size fits-all solutions in natural resource management, and responses to aquatic invasive alien species are no exception. The ways in which an invasive alien species interacts with its natural environment will vary across receiving watersheds. Moreover, the objectives associated with each unique invaded area may differ according to perspectives of local stakeholders, and especially when on traditional territories of different indigenous communities. Therefore, the management that results in the best outcomes across several objectives will not necessarily be the same across invaded ecosystems. Engaging in SDM for a number of invasive alien populations will take time and dedication (from several workshops to several years: McDaniels et al. 1999; Gregory et al. 2012) and the value of appropriately engaging stakeholders must be weighted against the need for rapid response (Simberloff 2003). For the reasons stated already, the benefits (reduced conflict, improved communication, buy-in to the response) due largely to improved stakeholder engagement, will be easier to achieve if time is invested in appropriate discussions with stakeholders (Novoa et al. 2018).

Invasive alien populations can represent a major threat to ecosystem structure and services. Determining whether, and how, to respond is challenging, especially given divergent views and objectives across stakeholders and agencies (Novoa et al. 2018). SDM offers a means of working with stakeholders to determine objectives, measures of success, various courses of action to eradicate or control the population and a clear, documented process to help with communication (Liu and Cook 2016). This process helps bridge the gap between science and communication (Shackleton et al. 2019), which should help reduce conflict among stakeholders or between stakeholders and agencies (Estevez et al. 2014; Shackleton et al. 2019). Spending less time and resources in conflicts should allow for a more focused effort at the overarching goal: dealing with invasive alien species and improving natural biodiversity.

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