Why do we map threats? Linking threat mapping with actions to make better conservation decisions

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Why do we map threats? Linking threat mapping with actions to make better conservation decisions

Vivitskaia JD Tulloch1,9, Ayesha IT Tulloch2,3, Piero Visconti4, Benjamin S Halpern5,6,7, James EM Watson2,8, Megan C Evans3, Nancy A Auerbach1, Megan Barnes1, Maria Beger1, Iadine Chadès9, Sylvaine Giakoumi1,10, Eve McDonald-Madden1,2,9, Nicholas J Murray1,9,11, Jeremy Ringma1 and Hugh P Possingham1,5

Spatial representations of threatening processes – “threat maps” – can identify where biodiversity is at risk, and are often used to identify priority locations for conservation. In doing so, decision makers are prone to making errors, either by assuming that the level of threat dictates spatial priorities for action or by relying primarily on the location of mapped threats to choose possible actions. We show that threat mapping can be a useful tool when incorporated within a transparent and repeatable structured decision-making (SDM) process. SDM ensures transparent and defendable conservation decisions by linking objectives to biodiversity outcomes, and by considering constraints, consequences of actions, and uncertainty. If used to make conservation decisions, threat maps are best developed with an understanding of how species respond to actions that mitigate threats. This approach will ensure that conservation actions are prioritized where they are most cost-effective or have the greatest impact, rather than where threat levels are highest.

Biodiversity is declining rapidly, as human activities drive global-scale species losses and ecosystem changes (Pimm et al. 2014). Conservation actions are required to protect species and ecosystems from the processes that imperil their existence (Figure 1; Panel 1). To manage threats to biodiversity, scientists and decision makers often rely on spatial data – traditionally the distribution of at-risk biodiversity – for prioritizing conservation decisions (Wilson et al. 2006). Focus has recently shifted toward understanding and incorporating the distribution of threats (Allan et al. 2013), and the costs of managing them (McCarthy et al. 2012). Static visualizations of the spatial distribution, intensity, frequency, or seasonality of threats to biodiversity across a landscape or seascapes are often referred to as “threat maps” (Figure 2; Neke and Du Plessis 2004; www.conservationgateway.org/Files/Pages/threat-maps.aspx). These maps are now regularly used to inform decisions about where to manage for biodiversity conservation and what actions to take (Figure 2; Salafsky et al. 2003), most notably identifying which regions to prioritize in terms of funding (eg Myers et al. 2000). But are threat maps the best tool for guiding conservation investment? Here we assess how threat maps have been used in the past, and how they should be applied in the future to maximize biodiversity outcomes.

Threat maps influence much of the prioritization of conservation efforts by scientists, non-governmental organizations (NGOs), and governments (Brooks et al. 2006). For example, Conservation International raised over US$750 million for conservation in their priority hotspots of high habitat degradation and species endemism (Myers and Worm 2003), while The Nature Conservancy has focused activities around global “crisis ecoregions” that have extensive habitat loss and limited protection (Hoekstra et al. 2005). The use and influence of threat maps in the scientific literature is growing exponentially (from two papers in 1993 to more than 100 in 2013; WebPanel 1). Approaches to threat mapping range from mapping the past or current distribution of a single threat (eg Schmidt et

In a nutshell:
- Threat maps are spatial representations of the distribution, intensity, or frequency of threats to biodiversity across a landscape or seascapes.
- Threat maps can be useful for informing where and why biodiversity is at risk but may be insufficient for informing efficient management actions.
- Using threat maps to guide conservation actions without clear management objectives linking to social, political, economic, or biodiversity outcomes can result in unintended consequences or misallocation of resources.
- Structured decision making (SDM) helps to evaluate potential management actions that might be taken in a threatened area, and can lead to more cost-effective conservation decisions.
- If applied to conservation-oriented decisions, threat mapping should be incorporated into SDM to account for the expected consequences of alternative strategies intended to promote biodiversity, so that the most effective threat-mitigating actions might be chosen.

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al. 2002), to identifying concentrations of endemic species that have experienced major threats in the past (eg hotspots; Myers et al. 2000), and more recently to additive scoring approaches for multiple threats, incorporating ecosystem vulnerability (Halpern et al. 2008).

Despite their potential advantages over species-based approaches and their frequent application (see examples in Table 1), the use of threat maps to guide the spatial implementation of conservation actions has notable limitations (eg Wilson et al. 2006). Doubts have been raised regarding whether and how threat maps should be considered in conservation-oriented management plans (Mace et al. 2000). We argue that, while useful in certain contexts, threat maps – including simple spatial overlays of threatened species or threat “hotspots” – may be insufficient for making cost-effective conservation decisions. In many cases,
alternative approaches that do not rely on threat maps will be required to better inform such decisions.

Decision theory: a strategic approach to prioritizing threat management

Decision theory is a rational systematic framework for choosing between different strategies and optimizing decisions with uncertain consequences (Possingham 2001). Structured decision making (SDM) is a rigorous, transparent, and iterative approach, grounded in decision theory (Gregory et al. 2012), which brings stakeholders together to solve problems by:

1. defining clear, quantifiable objectives and constraints related to the problem, and measurable attributes for each;
2. identifying a set of alternative management actions;
3. evaluating the consequences of alternative actions in terms of the objectives;
4. dealing explicitly with uncertainty; and
5. assessing trade-offs (Figure 3).

By explicitly identifying potential management actions and their outcomes, SDM aids in selecting actions that are expected to better achieve predefined conservation goals as compared with alternative actions. Historically, however, conservation organizations have often made management decisions based on threats rather than actions. For instance, Brooks et al. (2006) and Micheli et al. (2013) reviewed 21 different global or regional conservation prioritizations. While all considered the spatial distribution of threats or threatened species, none considered alternative actions or potential costs. In the absence of such considerations, it is impossible to identify species responses to actions and thus identify the optimal allocation of resources (eg conservation-oriented funding and personnel) between regions (Wilson et al. 2006). Although threat maps may serve as a useful public outreach tool to enhance funding opportunities for environmental organizations, there is often no explicit justification for using these maps to target (or ignore) certain threats or to inform conservation actions. Ultimately, conservation interventions should aim to deliver biodiversity outcomes. Decision-theoretic approaches such as SDM can identify actions that lead to the “best” outcomes (Polasky et al. 2011), rather than focusing on the locality of threats.

Here we adapt the steps of SDM to a threat mitigation decision problem (Figure 3; Gregory et al. 2012), highlighting where threat maps fit within the SDM framework and where they might fail to provide the information needed for action. We illustrate the differences between approaches that may or may not integrate threat maps with decision theory, and compare four different priority-setting approaches – where science was intended to inform decisions – for threatened species in Australia (WebPanel 2; [i] Australian Government 2003; [ii] Watson et al. 2011; [iii] Evans et al. 2011; [iv] Chadès et al. 2014). We use these examples to underscore potential flaws in the outcomes of threat-mapping approaches that did not formulate the decision problem from an SDM perspective (WebPanel 2, i–iii), and identify decision-theoretic approaches that can be used to maximize biodiversity outcomes (WebPanel 2, iv; WebTable 2).

Integrating threat management into an SDM framework

Step 1: set objectives, consider constraints, and assign measurable attributes

The initial step in SDM is to set clear objectives related to the focal problem and the desired outcomes (Gregory et al. 2012). These are essentially value judgments. In conserva-
In decision making, there are often multiple competing objectives related to social, political, economic, and biodiversity outcomes. Constraints associated with these objectives can affect management feasibility or outcomes. In SDM, constraints are considered during objective setting, with measurable attributes used to assess the consequences of different decisions (Martin et al. 2009), ensuring that decision making is driven by desired outcomes.

Too often in conservation contexts, there is only one objective: reduce or avoid threats. For example, three recent conservation priority-setting approaches all set different objectives to reduce threats to biodiversity in Australia (WebPanel 2, i–iii), and all prioritized different areas of the landscape. However, threat reduction is not a biodiversity outcome per se. By selecting threats to target before setting conservation objectives, organizations have a preconceived notion of how the species or system should be managed, and may cling to objectives (and actions) driven by information about the threat alone, rather than by the ultimate objectives. This mismatch can lead to the overall conservation objective being undermined. For instance, expanding protected areas because there are multiple threats and threatened species present in that area (WebPanel 2, ii) does not ensure positive outcomes for biodiversity, if there are threats that will continue despite that decision. Narrowly focused, threat-based objectives at best might achieve only the reduction of a single threat, and at worst may fail to minimize biodiversity loss because of unabated threats, action in inappropriate areas, or a lack of consideration of other socioeconomic or political constraints. In another example, to prioritize actions for conservation of rhinoceros species (black rhinoceros Diceros bicornis and white rhinoceros Ceratotherium simum) imperiled by illegal hunting, conservation programs set threat-based objectives such as “reducing poaching” (eg Zimbabwe Parks and Wildlife Management Authority 2003) using maps of recent poaching activities to increase militarized enforcement (eg www.stoprhinopoaching.com/statistics.aspx). However, focusing on actions that only try to mitigate the threat ultimately restricts supply of rhino horn, despite increasing market demand (Biggs et al. 2013). This raises the price of horn and provides incentives for poachers, resulting in perverse outcomes for biodiversity; many species, including rhinos, are still being poached at an increasing rate.

Outcome-oriented objective setting explicitly considers constraints such as time (eg over what temporal extent will costs and benefits be accrued), political context, governance (eg multi-jurisdictional issues), and budget limitations (eg minimizing costs or maximizing income) – factors usually overlooked in traditional threat-based approaches (eg WebPanel 2, i). SDM facilitates decisions that achieve positive outcomes by fully exploring the values and objectives of all stakeholders, typically in a stakeholder engagement process (eg WebPanel 2, iv; Gregory et al. 2012), rather than focusing on threat-based objectives.

<table>
<thead>
<tr>
<th>Table 1. Typology of mapping approaches used to make decisions for threatened species and systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output of approach</strong></td>
</tr>
<tr>
<td>Map of distribution of single species/ecosystem</td>
</tr>
<tr>
<td>Species “hotspots” (areas featuring high species richness, endemism, or rarity)</td>
</tr>
<tr>
<td>Species “hotspots” combined with threatening process</td>
</tr>
<tr>
<td>Map of single threatening process</td>
</tr>
<tr>
<td>Map of single threatening process linked to affected species</td>
</tr>
<tr>
<td>Map of multiple threatening processes (eg summed cumulative threat score/index)</td>
</tr>
<tr>
<td>Map of vulnerability of species, systems, or regions to threat</td>
</tr>
<tr>
<td>Map of impacts of multiple threatening processes on species/systems</td>
</tr>
</tbody>
</table>

Notes: Blue boxes indicate information used in the approach (see WebTable 1 for further details and additional references).
alone. Importantly, by considering constraints, SDM ensures that objectives are feasible given the political, cultural, or economic context; in extreme cases some potential actions will be impossible to implement.

Objectives need to be quantitative and unambiguous, and should represent all aspects of the conservation problem to be managed. For the rhino example, an outcome-oriented SDM objective might be to maximize the number of breeding rhinos, such as in the Namibian Government’s black rhino Conservation Strategy (Martin 2010). A measurable attribute could be rhino population viability after 20 years, which is linked directly to the desired outcome instead of the threat. Applying an SDM process might also identify human welfare as important; an additional objective might be to minimize income loss to local communities responsible for poaching. Examining outcomes, measurable attributes, and values thus helps to avoid the mismatch of objectives.

Finally, decisions based on threat maps are inherently scale dependent (Boyd et al. 2008); thus, international and national priorities guiding large-scale threat map development (such as WebPanel 2, i–iii) may not transfer to smaller-scale conservation decisions due to different species assemblages or policy settings (Guerrero et al. 2013). Because SDM can be scale independent, this problem can be overcome by matching the objectives (and associated actions) to the scale of the problem (eg WebPanel 2, iv).

**Step 2: develop management alternatives**

Many hypotheses, each of which could be linked to one or more potential management-related actions, may explain observed declines in biodiversity. In SDM, a set of all possible actions is developed, and constraints are considered; from the total list of potential actions, a subset is selected for further attention. By exploring alternative actions rather than a single action, managers may be better able to judge the pros and cons of each as they relate not only to biodiversity outcomes but also to ancillary political or socioeconomic outcomes (eg sustaining livelihoods; Pullin and Knight 2001). Managers can also better understand the benefits of multiple action strategies (Chadès et al. 2014). In the absence of such a comparison, it is impossible to assess potential trade-offs between different actions, a fundamental principle of cost-effective decision making. In the rhino example, SDM allows the supply-chain effects to be described because it canvases alternative options such as new policies or actions to decrease demand; this might lead to poaching being identified as an unstoppable threat that can be addressed only in combination with other alternative actions (such as intentional dehorning, education, or legalized harvesting; Figure 4; Biggs et al. 2013).

In WebPanel 2, the first example (i) failed to meet its objective to increase awareness of cost-effective conservation action because it did not link alternative actions or their costs to threats, an issue that can be resolved through decision-theoretic approaches (eg Joseph et al. 2009). The second approach (ii) is an improvement, given that the cost of protection was accounted for, but alternative actions were not developed. In the third example (iii), which still used a threat map, alternative actions were explored; this allowed for more cost-effective evaluation of outcomes. In the final case (iv), explicit consideration of costs and actions using an SDM approach enabled cost-effective investment in multiple actions, without utilizing threat maps.

Threat maps may be useful in identifying actions linked to threats (eg deforestation maps might inform actions such as conserving forest regrowth, promoting revegetation of previously forested lands, or enacting legislation to protect remnant vegetation). However, as in objective setting, decision makers relying on threat maps solely to manage direct threats risk implementing actions that only reduce a particular threat (such as expanding the spatial extent of existing protected areas; WebPanel 2, ii). There could, however, be many threats to biodiversity that are not mitigated by this action (Mora and Sale 2011). Without considering portfolios of actions, constraints, and consequences, a threat-based approach could – perversely – prioritize management efforts in inappropriate (due to displaced, diffuse, or unstoppable threats) or impractical (due to political, social, or economic reasons) areas or in locations degraded to such an extent as to render those efforts ineffectual (Figure 4; Game et al. 2008). Similarly, mapping the cumulative threats within a landscape or seascape (eg Halpern et al. 2008) may help to illustrate where actions are needed but cannot show which action should be taken. Furthermore, maps of unstoppable threats (eg ocean warming from cli-
mate change) are able to highlight only where direct action would be wasted (because local action cannot remove these threats; Figure 4); such maps should not be used to set priorities. By listing actions rather than threats, SDM automatically avoids addressing unstoppable threats and instead directs resources toward actions that encourage positive biodiversity or socioeconomic outcomes (Figure 4).

**Step 3: estimate consequences**

Once Steps 1 and 2 have been completed, SDM practitioners must identify how outcomes contribute to the desired objective. This step requires understanding how biodiversity features and associated threats may respond to an action (including its spatial extent, intensity, frequency, or duration) but also understanding what would have happened in the absence of an action (ie estimating “additionality”; Maron et al. 2013). For biodiversity objectives, benefits are most often measured in terms of biodiversity outcomes (eg increases in population growth rate or population size); by way of comparison, economic-related benefits are measured in currency and threat-related benefits are measured in terms of how much the threat was mitigated.

The effectiveness of actions to ameliorate threats will vary. Although informing the likely outcome of inaction, threat maps fail to inform decision makers about the consequences of various actions. Without understanding consequences, decision makers cannot judge the relative benefits of implementing alternative actions. Indeed, threat maps might lead to threat mitigation in areas considered the most threatened rather than in areas where actions will be most effective. For the rhino example, linking population viability to the level of mitigated poaching allows decision makers to predict whether reductions in poaching might achieve a desired outcome, as compared with how new policies, such as legalized harvesting, might affect supply and demand (Biggs et al. 2013). Prioritizing rhino conservation in areas with the greatest number of known poachers may not lead to desired outcomes if the demand for horn has not declined.

Species’ populations may respond positively, negatively, or neutrally – in terms of increasing, decreasing, or unchanged abundance – to certain threats and actions (Díaz et al. 2013). Most threat maps assume additive responses to multiple threats (eg Halpern et al. 2008); however, antagonistic or synergistic interactions and responses are possible (Brown et al. 2013). By choosing an ineffective management action, managers may squander limited funding (Walsh et al. 2012) while failing to understand why biodiversity continues to decline (see Figure 4). For example, establishing protected areas (WebPanel 2, ii) will not counteract species losses due to trophic effects of invasive animals (WebPanel 2, iii); this requires different management actions, such as introducing population control measures through intentional poison bait campaigns. Determining relationships – between threats and conservation actions, between actions and biodiversity outcomes, and between outcomes and money invested, as well as the links among these relations – is vital for selecting cost-effective actions (Carwardine et al. 2012).

A range of approaches can be used to describe the con-
sequences of a conservation action (see examples in WebTable 2). These may or may not link spatially to the distributions of threats, depending on whether this information can be derived. Process models that describe biodiversity responses to management approaches (eg population models and viability analysis; WebTable 2; Possingham et al. 1993) are frequently used in SDM (eg Mitchell et al. 2013) but are more likely to be linked to species distributions rather than threats (eg Falcucci et al. 2009). Increasingly, return-on-investment thinking that uses empirical data on benefits and costs of actions (WebTable 2; Murdoch et al. 2007), or expert elicitation of the likelihood of successful management of species where empirical data are lacking (WebTable 2; Joseph et al. 2009), is used to predict consequences of alternative management actions (see also WebPanel 2, iv). After calculating the consequences of mitigation, it is more useful to target distributions of biodiversity than distributions of threats (eg Maggini et al. 2013). Predicting such consequences will ideally identify actions that would minimize the likelihood of extinction and clarify the mechanisms driving species responses.

**Step 4: address uncertainty**

In threat management, uncertainty – our lack of knowledge about which species to protect and where – pervades every decision. The amount of information we are missing (parameter uncertainty), or the likelihood that our understanding of the system is incorrect (model uncertainty), may be difficult to quantify (Regan et al. 2005; Gregory et al. 2012). By explicitly accounting for the uncertainties pervasive in decision making, decision-theoretic approaches such as SDM make it possible to maximize the expected return in the face of uncertain parameters and models, or to minimize the consequences of the worst-case scenarios (Regan et al. 2005). Assigning a feasibility value to outcomes (to account for the likelihood of an action being successful), or a certainty weighting to expert elicited data (to elucidate how confident we are in the information), allows further exploration of the risks of different decisions. Setting upper and lower bounds on parameters can highlight the best-case and worst-case scenarios rather than a single outcome. Failing to associate uncertainty bounds with the presence and intensity of threats to biodiversity prevents decision makers from comparing the expected return on alternative investments and essentially from making informed decisions (Wilson et al. 2006; Visconti et al. 2010). Although consideration of uncertainty is inherent in SDM (Figure 3), few threat-mapping prioritizations address this issue (however see Carvalho et al. 2011). If not explicitly incorporated in all stages of the mapping and decision-making process, uncertainty will increase costs as well as the probability of selecting an unsuccessful conservation action (Figure 4).

It is impossible to account for all the uncertainties associated with different threats; however, quantitative maps that link multiple threats with the probability of successful management (see WebTable 2) might allow evaluation of total management costs and an exploration of the distribution of effort required across a landscape (Auerbach et al. 2014). This directly links with Steps 2 (evaluating alternatives) and 5 (assessing trade-offs) of the SDM process (Figure 3).

**Step 5: assess trade-offs and select decision**

To resolve conservation problems, SDM practitioners assess trade-offs between stated objectives to prioritize and ultimately select appropriate actions. The assessment process is iterative and must simultaneously consider costs, feasibility, and benefits (Wilson et al. 2010). Actions are then prioritized based on the likelihood of achieving multiple objectives, such as maximizing species abundance while minimizing costs (WebPanel 2, iii and iv). Threat maps alone are insufficient to account for trade-offs inherent in conservation decision making. For instance, referring to a threat map with additively combined information on individual threats would not allow decision makers to consider trade-offs that might exist between particular threats and their associated actions. By determining the consequences of all alternative actions rather than focusing on threats, decision-theoretic approaches (see WebTable 2 for examples) avoid this dilemma, as they allow for multiple solutions. By using an SDM framework it is possible to determine how to manage interacting species simultaneously; in cases where managing one species differentially affects other species, multiple objectives might be required (eg maximizing the persistence of one species while minimizing population losses for another; Díaz et al. 2013; Tulloch et al. 2013a). For highly migratory species, it may not be feasible to mitigate threats outside of managed areas that are characterized by different governance and political contexts (Nicol et al. 2013). Weighting values, consequences, and objectives helps assess trade-offs in multi-action decision making (eg Multiple Criteria Decision Analysis; WebTable 2; Walshe and Burgman 2010), and ensures that societal preferences or constraints are accommodated.

- Threat maps are not a panacea: improvements to using threat maps for decision making

To ensure that decisions are made quickly and effectively and to avoid costly mistakes when prioritizing conservation efforts, we have shown how and when threat mapping might be applied in conservation decision making. By understanding the limitations of threat maps, decision makers can decide whether it is more important to learn about what is happening in a landscape (when threat maps are most useful) or to implement management actions (when threat maps are not always useful).

Several emerging decision-theoretic techniques for
informing conservation decisions may account for threats and their inherent uncertainty without using fine-scale, spatially explicit data, as is the case in traditional single or additive threat maps (see examples in WebTable 2). If threat maps are to inform management decisions, spatially explicit response curves linking actions directly with threats could be useful; however, these are difficult to develop due to the high level of parameterization and resolution required (Kelly et al. 2012). Recently, population models have been coupled with species distribution models and threat distribution to investigate expected responses by populations to changing threats and likely actions (eg Regan et al. 2012). Alternatives to the conventional approach of additive threat mapping depend on the problem scale and constraints. Furthermore, the actions required will influence the analytic approach used to inform decision making: some management options will be a one-off action (eg buying land) and are relatively simple to solve through the use of systematic conservation planning and static threat maps, whereas other options will require ongoing action (and costs) and therefore represent more complex temporal approaches (eg managing disease spread using Markov Decision Processes) (WebTable 2; Chadès et al. 2011).

Although important, threat maps are insufficient for choosing which action to take in a given location. SDM can include the use of threat maps but also considers other factors vital for effective threat management. Given increasingly limited conservation funds, incorporating threat mapping into decision-theoretic frameworks will lead to improved management outcomes by accounting for uncertainty and species responses, in addition to the cost, feasibility, and consequences of actions. The use of an SDM framework to solve complex conservation problems will ensure not only transparency and accountability of decisions but also that actions are prioritized in locations where the best outcomes for biodiversity can be achieved.

Acknowledgements

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References


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† These authors contributed equally to this work.
WebPanel 1. Results of Web of Science search conducted on 31 December 2013.

- Search in Web of Science for the words “threat*” and “map*” and “conserv*”:
  811 (average citations per item: 16.21)

<table>
<thead>
<tr>
<th>Published items per year</th>
<th>Citations per year</th>
</tr>
</thead>
<tbody>
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</table>

- Refined with word “action”:
  81 (average citations per item: 16.01)

<table>
<thead>
<tr>
<th>Published with “action”</th>
<th>Citations with “action”</th>
</tr>
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<tbody>
<tr>
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</table>

- Refined with word “decision”:
  82 (average citations per item: 16.00)

<table>
<thead>
<tr>
<th>Published with “decision”</th>
<th>Citations with “decision”</th>
</tr>
</thead>
<tbody>
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<td></td>
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</tbody>
</table>
WebPanel 2. Case studies of different approaches to prioritizing threats in Australia

These case studies highlight the increasing usefulness of decision outcomes for conserving biodiversity (from left to right), given increasing integration within SDM. Section (i) represents a threat map, directing investment to blue areas; this is a process that is severely limited in what it can do to inform management. Section (ii) shows the assimilation of a threat map in SDM giving a binary choice: protect (in black) versus do not protect (white). Section (iii) depicts the assimilation of threat maps in SDM, incorporating trade-offs and uncertainty, and directing low, medium, or high levels of investment to management for two threats. Finally, section (iv) illustrates a sophisticated SDM process using cost-effectiveness analysis that does not need or use a threat map to direct investment to multiple actions.

<table>
<thead>
<tr>
<th></th>
<th>(i)</th>
<th>(ii)</th>
<th>(iii)</th>
<th>(iv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal of prioritization</td>
<td>Australian Government (2003)</td>
<td>Increase awareness of cost-effectiveness of strategic timely action to conserve Australian biodiversity</td>
<td>Determine how much more protected area is required to protect all Australian threatened species</td>
<td>Identify priorities for investment in management actions to abate multiple threats across Australia</td>
</tr>
<tr>
<td>Objective</td>
<td>Identify hotspots where species are under high levels of threat (outcome measured by level of mitigated threat)</td>
<td>Minimize cost of protection while achieving threatened species targets (outcome measured by species richness, unrelated to effectiveness of action)</td>
<td>Maximize number of species protected by investing in multiple conservation actions with specified timescale and budget</td>
<td>Maximize number of species persisting in the landscape and minimize the cost</td>
</tr>
<tr>
<td>Biodiversity objective outcome-oriented?</td>
<td>No</td>
<td>No</td>
<td>Yes - Final outcome measured in terms of species persistence relative to effectiveness of action</td>
<td>Yes - Final outcome measured in terms of species persistence relative to effectiveness of action</td>
</tr>
<tr>
<td>Actions and alternatives</td>
<td>No</td>
<td>Single action: Protected area designation</td>
<td>Multiple actions: direct fox control (baiting), direct rabbit control (baiting, warren ripping, and fumigation), combined fox and rabbit control</td>
<td>Multiple actions (“strategies”) and action combinations (to account for dependencies/interactions between threats and actions)</td>
</tr>
<tr>
<td>Consequence of action</td>
<td>No</td>
<td>Only cost of action (assumes action is 100% successful)</td>
<td>Return-on-investment (benefits = number of species likely to respond to management; costs = do one or both actions)</td>
<td>Probability of response to threat mitigation in relation to different persistence objectives and different budgets</td>
</tr>
<tr>
<td>Uncertainty incorporated?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes - Probabilistic species responses and action feasibilities are considered</td>
</tr>
<tr>
<td>Trade-offs</td>
<td>No</td>
<td>No</td>
<td>Fox, rabbit, or combined management selected according to whether benefits outweighed costs</td>
<td>Species saved versus costs incurred</td>
</tr>
<tr>
<td>Threats mapped?</td>
<td>Areas with many endemic species and high levels of stress or future threat (habitat loss) identified as hotspots for priority conservation</td>
<td>Threatened species distributions mapped; areas with most threatened species prioritized using cost layer (all threats considered equal)</td>
<td>Threat distributions modeled - species distributions surrogates for threats affecting them (invasive foxes, rabbits); areas prioritized based on highest value of benefit of acting on threat</td>
<td>No - Expert elicitation, cost-effectiveness analysis to rank actions, multi-objective optimization</td>
</tr>
<tr>
<td>Outcomes</td>
<td></td>
<td></td>
<td></td>
<td>Actions prioritized across entire landscape; solutions provide ranking of most-effective actions for all sub-regions considered</td>
</tr>
</tbody>
</table>
**WebTable 1. Additional references to support Table 1**

<table>
<thead>
<tr>
<th>Approach</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution of single species/ecosystem</td>
<td>Range maps of species and their risk of extinction (IUCN 2013)</td>
</tr>
<tr>
<td>Species “hotspots” (areas featuring high species richness, endemism, or rarity)</td>
<td>Global biodiversity hotspots of combined species richness, endemism, and endangerment (Ceballos and Ehrlich 2006); Global hotspots of high plant species endemism in tropical wilderness areas (Mittermeier et al. 1998)</td>
</tr>
<tr>
<td>Species “hotspots” combined with threatening process</td>
<td>Global hotspots of habitat degradation and species endemism (Myers et al. 2000); Global hotspots of habitat loss with limited protection from reserves (Hoekstra et al. 2005)</td>
</tr>
<tr>
<td>Map of single threatening process</td>
<td>Global maps of threats to marine systems (eg coral bleaching; Jameson et al. 1995); Invasive species (eg foxes in Australia [DPIPWE 2012; Sarre et al. 2012])</td>
</tr>
<tr>
<td>Map of single threatening process linked to species</td>
<td>Poaching risk map (Sánchez-Mercado et al. 2008); Road mortality (Beaudry et al. 2008; Eberhardt et al. 2013)</td>
</tr>
<tr>
<td>Map of multiple threatening processes (eg summed cumulative threat score/index)</td>
<td>Summed scores of cumulative threats from human influence (ie population, land tenure, urbanization, roads, etc; Kram et al. 2012); Human footprint mapping (Sanderson et al. 2002; McKee et al. 2004); Reefs at risk from multiple human threats (Burke and Maidens 2003; Burke et al. 2011)</td>
</tr>
<tr>
<td>Vulnerability or resilience of species or systems to threatening processes</td>
<td>Vulnerability/resilience maps of species/systems (Wallace et al. 2011; Fuentes et al. 2013); Coastal vulnerability to sea-level rise (Nicholls and Cazenave 2010); Species distribution, climate-change modeling, and expert assessment used to determine species vulnerability to threat (Schlesinger et al. 2011)</td>
</tr>
<tr>
<td>Map of multiple threatening processes and distributions of species/ecosystems (eg summed threat impact score/index)</td>
<td>Summed threat impact score (multiple human threats) across different marine ecosystems (Halpern et al. 2008; Selkoe et al. 2009); Additive hotspots of threats and species richness (Hof et al. 2011); Summed scores of threat indicators to identify vegetation condition across tropical Queensland (Pert et al. 2012); Spatial distribution of species by threat (Evans et al. 2011b)</td>
</tr>
</tbody>
</table>
### WebTable 2. Approaches to evaluate trade-offs and select actions, which can be used in structured decision making (Step 5, Figure 3)

<table>
<thead>
<tr>
<th>Approach</th>
<th>Decision-theoretic concepts addressed by approach</th>
<th>Limitations of approach</th>
<th>Uses a threat map</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threat mapping</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Population viability analysis (PVA)</td>
<td>x</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Decision tree analysis</td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Bayesian Belief Network (BBN)</td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Cost-effectiveness analysis to rank conservation actions</td>
<td></td>
<td></td>
<td>Sometimes</td>
</tr>
<tr>
<td>Return on investment (ROI) framework</td>
<td></td>
<td></td>
<td>Sometimes</td>
</tr>
<tr>
<td>Stochastic dynamic programming/adaptive management (eg Markov Decision Processes [MDP]/Partially Observable Markov Decision Processes [POMDP])</td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Multiple Criteria Decision Analysis (MCDA)</td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Info-gap models</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Systematic conservation planning tools, including uncertainty and threat (eg Marxan with Probability, Zonation)</td>
<td></td>
<td></td>
<td>Yes</td>
</tr>
<tr>
<td>Management strategy evaluation (MSE) using operating models (eg multi-species/process models)</td>
<td></td>
<td></td>
<td>Sometimes</td>
</tr>
</tbody>
</table>

**Notes:** These tools provide alternatives to or enhance threat mapping. Shaded boxes represent how well the tool addresses the issues that manifest with threat mapping when SDM is forgone (red = always help with issue, yellow = may help with issue, purple = unable to help with issue), with “x”s indicating limitations (references in WebTable 3).
### WebTable 3. Supporting information for WebTable 2

<table>
<thead>
<tr>
<th>Approach</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision tree analysis</td>
<td>Salzer and Salafsky (2006); Hoegh-Guldeberg et al. (2008)</td>
</tr>
<tr>
<td>Bayesian Belief Network (BBN)</td>
<td>Newton et al. (2007); Rumpff et al. (2011)</td>
</tr>
<tr>
<td>Cost-effectiveness analysis of conservation actions</td>
<td>Joseph et al. (2009); Walshe and Burgman (2010); Carwardine et al. (2012, 2014); Martin et al. (2012)</td>
</tr>
<tr>
<td>Return on investment (ROI) framework</td>
<td>Wilson et al. (2007); Underwood et al. (2008); Wintle et al. (2011); Auerbach et al. (2014)</td>
</tr>
<tr>
<td>Population Viability Analysis (PVA)</td>
<td>Lindenmayer and Possingham (1996); Bakker et al. (2009); Bode and Brennan (2011); Wintle et al. (2011)</td>
</tr>
<tr>
<td>Stochastic dynamic programming/adaptive management (eg Markov Decision Processes [MDP]/Partially Observable Markov Decision Processes [POMDP])</td>
<td>Hauser and Possingham (2008); Chadès et al. (2011); Chadès et al. (2012); Nicol and Chadès (2012)</td>
</tr>
<tr>
<td>Multiple Criteria Decision Analysis (MCDA)</td>
<td>Martin et al. (2009); Walshe and Burgman (2010); Forsyth et al. (2012); Gregory et al. (2012); Chadès et al. (2014)</td>
</tr>
<tr>
<td>Info-gap models</td>
<td>Ben-Haim (2001)</td>
</tr>
<tr>
<td>Systematic conservation planning tools including uncertainty and threat (eg Markov decision processes and Zonation)</td>
<td>Araujo et al. (2005); Moilanen and Cabeza (2005); Game et al. (2008); Klein et al. (2013)</td>
</tr>
<tr>
<td>Management strategy evaluation (MSE) using operating models (eg multi-species/process models)</td>
<td>Milner-Gulland (2011)</td>
</tr>
</tbody>
</table>

**Notes:** Approaches for evaluating trade-offs and select actions, which can be used in Structured Decision Making (Step 5, Figure 3), that provide alternatives to or enhance threat mapping.

### WebReferences


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