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Contributed Paper

Setting conservation management thresholds using a novel participatory modeling approach

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Abstract: *We devised a participatory modeling approach for setting management thresholds that show when management intervention is required to address undesirable ecosystem changes. This approach was designed to be used when management thresholds: must be set for environmental indicators in the face of multiple competing objectives; need to incorporate scientific understanding and value judgments; and will be set by participants with limited modeling experience. We applied our approach to a case study where management thresholds were set for a mat-forming brown alga,* Hormosira banksii*, in a protected area management context. Participants, including management staff and scientists, were involved in a workshop to test the approach, and set management thresholds to address the threat of trampling by visitors to an intertidal rocky reef. The approach involved trading off the environmental objective, to maintain the condition of intertidal reef communities, with social and economic objectives to ensure management intervention was cost-effective. Ecological scenarios, developed using scenario planning, were a key feature that provided the foundation for where to set management thresholds. The scenarios developed represented declines in percent cover of* H. banksii *that may occur under increased threatening processes. Participants defined 4 discrete management alternatives to address the threat of trampling and estimated the effect of these alternatives on the objectives under each ecological scenario. A weighted additive model was used to aggregate participants' consequence estimates. Model outputs (decision scores) clearly expressed uncertainty, which can be considered by decision makers and used to inform where to set management thresholds. This approach encourages a proactive form of conservation, where management thresholds and associated actions are defined a priori for ecological indicators, rather than reacting to unexpected ecosystem changes in the future.*

Keywords: expert elicitation, management threshold, scenario planning, state-dependent management, structured decision making, uncertainty

Establecimiento de Umbrales de Manejo de Conservación con el Uso de una Estrategia Novedosa de Modelación Participativa

Resumen: *Diseñamos una estrategia de modelación participativa para establecer umbrales de manejo que muestren cuando se requiere de intervención en el manejo para tratar con cambios indeseables en los ecosistemas. Esta estrategia se diseñó para ser usada cuando los umbrales de manejo: deban estar fijados para los indicadores ambientales de frente a múltiples objetivos en competencia; necesiten incorporar al entendimiento científico y a los juicios de valor; sean fijados por participantes con experiencia limitada en la modelación. Aplicamos nuestra estrategia a un estudio de caso en el que los umbrales de manejo estaban fijados para una alga café formadora de tapetes,* Hormosira banksii*, en un contexto de manejo de área protegida. Los participantes, incluidos el personal de manejo y los científicos, estuvieron involucrados en un taller para probar la estrategia y establecieron los umbrales de manejo para tratar la amenaza del pisoteo por los visitantes para un arrecife rocoso inter-mareal. La estrategia involucró el intercambio del objetivo ambiental (mantener las condiciones de las comunidades del arrecife inter-mareal) por objetivos*

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sociales y económicos para asegurar que la intervención del manejo fuera rentable. Los escenarios ecológicos, desarrollados usando la planeación de escenarios, fueron una característica clave que proporcionó la base para ubicar los umbrales de manejo. Los escenarios desarrollados representaron declinaciones en el porcentaje de cobertura de H. banksii *que podrían ocurrir bajo procesos crecientes de amenaza. Los participantes definieron cuatro alternativas discretas de manejo para tratar la amenaza del pisoteo y estimaron el efecto de estas alternativas sobre los objetivos bajo cada escenario ecológico. Se usó un modelo aditivo ponderado para añadir los estimados de consecuencia de los participantes. Los resultados del modelo (puntajes de decisión) expresaron claramente la incertidumbre, lo que puede ser considerado por quienes toman las decisiones y utilizado para informar dónde ubicar los umbrales de manejo. Esta estrategia fomenta una forma proactiva de conservación, en la cual los umbrales de manejo y las acciones asociadas son definidas a priori por los indicadores ecológicos, en lugar de reaccionar a futuros cambios inesperados en los ecosistem*

Palabras Clave: incertidumbre, manejo dependiente del estado, obtención de información de expertos, planeación de escenarios, toma estructurada de decisiones, umbral de manejo

Introduction

Conservation management agencies aspire to safeguard species, ecosystems and habitats from undesirable change. State-dependent management is one useful approach, where monitoring data are used to assess whether a protected system is shifting into an undesirable state and management intervention is required to address this change (Nichols & Williams 2006; Lyons et al. 2008). A proactive application of state-dependent management involves the use of management thresholds, which represent when management intervention is required to address undesirable ecosystem changes. Management thresholds have had widespread application in natural resource management, including species harvest management (Nichols et al. 2007) and water quality management (ANZECC 2000). However, there are fewer applications of management thresholds to enable state-dependent management in conservation (Groffman et al. 2006; Martin et al. 2009). Consequently, there have been instances where programs have monitored species of conservation value until they became extinct without triggering adequate or timely management intervention (Lindenmayer et al. 2013).

The discussion around thresholds in the conservation literature has been dominated by ecological thresholds, representing a point of rapid or irreversible ecosystem change (Groffman et al. 2006). The inherent complexity of ecological systems means that ecological thresholds can be difficult to identify or may not exist in some systems. The pursuit of ecological threshold identification can detract from setting management thresholds that represent where timely and cost-effective management intervention is required to prevent undesirable ecosystem changes (Bennetts et al. 2007; Martin et al. 2009).

There are limited published examples of management thresholds that enable state-dependent management in conservation. Identifying thresholds of potential concern is one approach that builds on the level of acceptable natural variability of ecological attributes. In South Africa, such thresholds have been used to identify when management intervention should occur and enable the adaptive management of national parks (Biggs & Rogers 2003). An alternative approach is the use of statistically derived management thresholds that promote careful consideration of statistical issues associated with interpreting monitoring data and that facilitate the proactive management of environmental systems (Field et al. 2004; Morrison 2008). These approaches focus on the environmental dimension of setting management thresholds for environmental indicators in isolation of competing socio-economic factors. They are useful in contexts where environmental objectives are the sole driver of conservation efforts; however, many complex conservation decisions must be made in the face of competing environmental, social, and economic objectives (Game et al. 2013).

Structured decision making can assist with setting management thresholds for multi-objective conservation decisions. It involves a series of steps that incorporates both scientific knowledge and values into decision making and acknowledges that decision making is not a value-free process (Failing et al. 2007). Structured decision-making also promotes the involvement of decision makers, stakeholders, and experts (collectively participants) in decision making (Gregory et al. 2012). The 2 published examples of use of structured decision making to develop management thresholds involved the application of stochastic dynamic programming to model ecosystem behavior and set optimal management thresholds for environmental indicators in the face of competing objectives (Martin et al. 2009, 2011). This approach is particularly effective when quantitative modeling expertise is available and participants with some modeling experience are involved in setting management thresholds. However, such modeling approaches can appear unintuitive or illogical to those without quantitative modeling expertise, and in these situations more transparent and collaborative techniques may be more appropriate (Addison et al. 2013).

We sought to introduce a novel modeling approach in response to the need for setting management thresholds in the face of competing objectives, with a focus on providing accessible tools to engage participants with limited modeling experience.

A single approach to setting management thresholds will not be suitable in all situations because conservation decisions often involve different circumstances that require different modeling approaches (Addison et al. 2013). We propose this participatory modeling approach as one in a toolbox of available approaches to assist with setting management thresholds. Our approach is particularly relevant in situations when management thresholds must be set for environmental indicators in the face of multiple competing objectives; need to incorporate scientific understanding and value judgments about the management of the ecosystem; or must be set by participants with limited modeling experience. To illustrate this approach, we used a multi-objective case study aimed at setting management thresholds in a protected area management context.

Methods

Participatory Modeling Approach to Set Management Thresholds

We illustrate a participatory modeling approach that draws on a unique combination of techniques that have not been used to set conservation management thresholds to date. The approach is framed within a structured decision-making framework (Fig. 1). The 6 steps and supporting techniques of our approach are outlined below.

Step 1. Clarify the decision context

Management thresholds are only relevant when there is a commitment to state-dependent management of a system. Thus, the decision context must be clarified to determine if long-term monitoring data will be used for state-dependent management (Fig. 1). A well-defined decision context should also include a description of the temporal and spatial scale for management, the ecosystem dynamics of the system, and potential or known threatening processes. Group discussion and conceptual models can help define the decision context because they capture the collective understanding of the dynamics of the managed system and management constraints (Sandker et al. 2010; Biggs et al. 2011).

Step 2. Define management objectives and alternatives

Management objectives should be specific, with quantifiable outcomes that reflect participants' values, and can reflect environmental, social, and economic values that are considered directly relevant to the decision context (Runge & Walshe 2014). Management objectives can be defined using value-focused thinking, which encourages participants to consider what they fundamentally care about (Keeney 1992). An objectives hierarchy can be used to facilitate the identification of fundamental objectives and can further help participants identify performance measures for each management objective (Clemen 1996). Performance measures determine whether management objectives are being achieved and include an indicator, unit of measure, and preferred direction (e.g., maximize or minimize). During this stage the key ecological indicator or indicators to be monitored and assessed using management thresholds must be defined.

Management alternatives represent discrete, feasible management approaches to meet objectives over the management horizon (Runge & Walshe 2014), which should include the status quo (management actions currently being undertaken) and do nothing (no active management) (Gregory et al. 2012). Value-focused thinking (Keeney 1992) and conceptual models (Biggs et al. 2011) can be used to explore the threatening processes and drivers acting on objectives, and thus help participants identify management alternatives.

Step 3. Develop ecological scenarios

Ecological scenarios are a key feature of this approach that provide the foundation for where to set management thresholds. Ecological scenarios represent plausible future states of the key ecological indicator that may occur under increased threatening processes and account for uncertainty and complexity associated with future trajectories of natural systems. Scenario planning can help define ecological scenarios by guiding participants through a creative thinking exercise about plausible future states of a natural system, the development of creative management alternatives to address future unfavorable states, and estimating the effectiveness of management alternatives under a variety of future states (Schoemaker 1995; Peterson et al. 2003). Scenario planning typically draws on conceptual models, empirical evidence, and participants' expert judgment about undesirable ecosystem conditions. This information can then inform quantitative levels of the key ecological indicator that form the basis of the different ecological scenarios. The ecological scenarios developed are used throughout the remainder of the participatory modeling approach to identify conditions of the ecological indicator where the management should change and thus where the management threshold or thresholds should be set.

Step 4. Estimate consequences and explore trade-offs

In the absence of targeted epirical evidence, expert judgement can be used to evaluate the consequences of management alternatives on each management objective. Participants provide quantitative consequence estimates that reflect their conceptual understanding, supported by empirical evidence when available, of the cause-and-effect relationships under each ecological

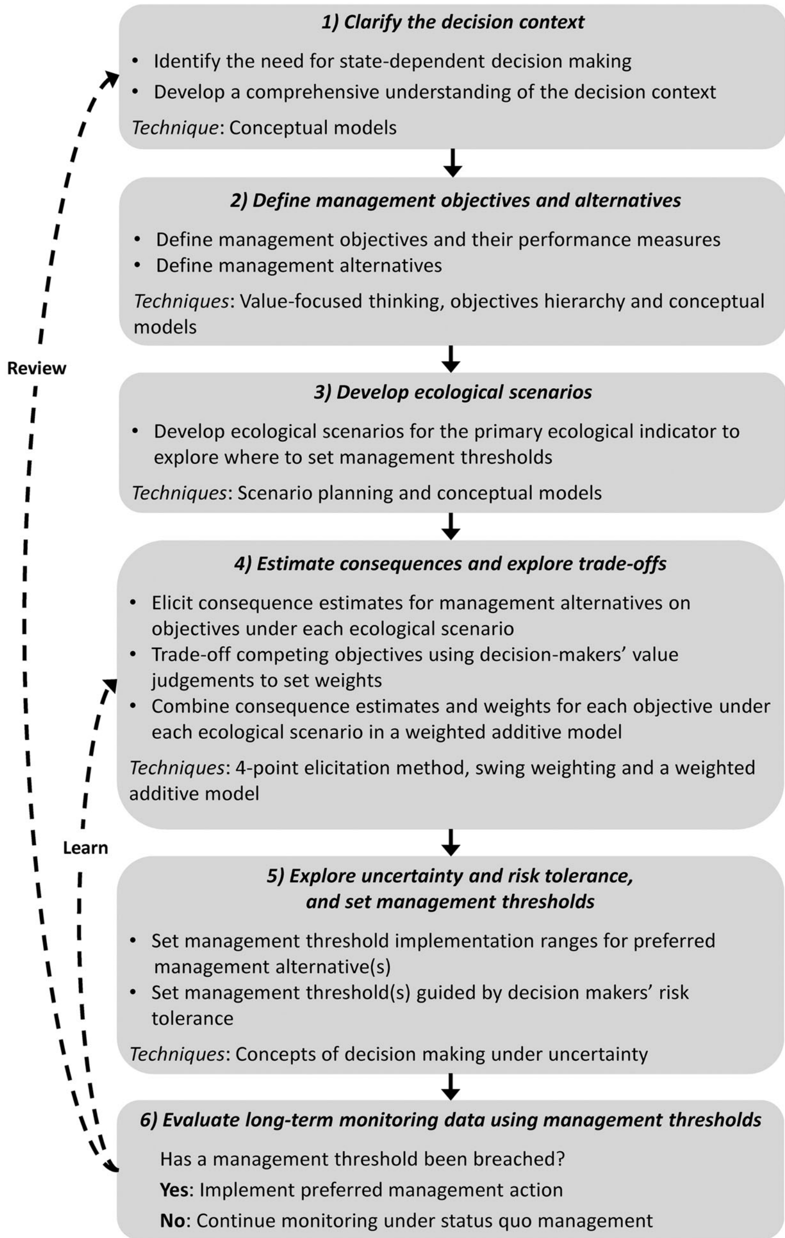

Figure 1. The steps of the participatory modeling approach and recommended techniques to set management thresholds.

scenario. During this stage the time frame of the estimated consequences of the management alternatives on objectives must be defined (i.e., x years after the implementation of management alternatives). To capture the uncertainty in participants' judgments, optimistic and pessimistic consequence estimates should be elicited together with their best estimates and participants should articulate the degree of confidence that the nominated interval encloses the truth (e.g., 4-point elicitation method) (Speirs-Bridge et al. 2010).

When multiple competing objectives are encountered in decision making, a formal trade-off step is required. Techniques used in multi-attribute utility theory are useful here because these are designed to assist with evaluating complex multi-objective decisions (von Winterfeldt & Edwards 1986; Belton & Stewart 2002). To trade-off competing objectives, decision makers must weigh the relative importance of each management objective. Weights can be elicited using a variety of techniques (e.g., direct rating, swing weights, cross-attribute indifference) (von Winterfeldt & Edwards 1986). A widely advocated technique is the swing weight method because this is considered very effective and simple to implement when working with participants (von Winterfeldt & Edwards 1986). The swing weight method involves showing participants the full range of consequence estimates for each objective (minimum pessimistic consequence estimate versus maximum optimistic consequence estimate) and asking participants to assign weights to each objective. Weights reflect the order of preference: a weight of 100 is given to the most valued objective and a weight of zero is assigned to objectives that have no perceived value.

To aggregate the consequence estimates and weights of the objectives and obtain an overall evaluation of management alternatives, multi-attribute value theory commonly calls on the use of a simple additive model (although more complex models exist [von Winterfeldt & Edwards 1986]). The multi-objective decision score for each management alternative (V_i) under each ecological scenario is

$$V_i = \sum_{j=1}^{n} w_j x_{ij}, \qquad (1)$$

where w_j is the normalized weight assigned to objective j and x_{ij} is the normalized consequence for alternative i on objective j. The consequence estimates (x_{ij}) are normalized (on a scale of 0 to 1) across the range of the estimated consequences of each objective with

$$x_{ij} = \frac{x_i - x_{\mathrm{min(pessimistic)}}}{x_{\mathrm{max(optimistic)}} - x_{\mathrm{min(pessimistic)}}}, \qquad (2)$$

where $x_{\mathrm{max(optimistic)}}$ is the maximum optimistic estimate and $x_{\mathrm{min(pessimistic)}}$ is the minimum pessimistic estimate across all ecological scenarios.

The weighted additive model is used to generate 3 estimates for each management alternative under each ecological scenario: a nominal decision score (based on the participants' best guess estimates); a lower bound decision score (based on the participants' pessimistic estimates); and an upper bound decision score (based on the participants' optimistic estimates).

Step 5. Explore uncertainty and risk tolerance and set management thresholds

The weighted additive model outputs (decision scores) are used to determine the preferred management alternative under each ecological scenario. Following the concept of decision making under uncertainty (Chankong & Yacov 1983), decision makers can interpret decision score plots for each ecological scenario based on 1 of 3 rules: best guess, pessimistic, or optimistic. The best-guess rule involves selecting the best performing management alternative under each scenario based on the highest nominal decision score (ignores the uncertainty surrounding the nominal decision score). The pessimistic rule involves selecting the best performing management alternatives under each scenario based on the lower bound decision score (assumes the worst payoff will eventuate for a management alternative). The optimistic rule involves selecting the best performing management alternatives under each scenario based on the upper bound decision score (assumes the best payoff will eventuate for a management alternative).

The preferred management alternative selected under each scenario informs where to set the management threshold implementation range or ranges. Management threshold implementation ranges illustrate where the most effective management action should be implemented, and importantly where a change in management intervention is required as the condition of the ecological indicator declines.

To set a management threshold, decision makers can be guided by the management threshold implementation range or ranges. The final decision to set a management threshold will reflect a decision makers' risk tolerance associated with the decision context. A risk-averse decision maker will set a management threshold toward the maximum value of the implementation range, whereas a risk-seeking decision maker may set a management threshold toward the minimum value of the implementation range.

Step 6. Evaluate long-term monitoring data using management thresholds

Long-term monitoring data should be regularly evaluated against management thresholds. If a management threshold is breached, the associated management action should be implemented. If a management threshold has not been breached, monitoring should continue under the preferred management. The learn-and-review feedback loops encourage the recurrent nature of state-dependent management to assist with clarifying uncertainty associated with model parameters, evaluating the true effectiveness of management interventions, and revising the decision context where necessary (Fig. 1).

Case Study

This participatory modeling approach was trialed using a case study involving the management of an intertidal reef in a marine national park (MNP) in Victoria, Australia. The management agency responsible for managing Victorian MNPs intends to conduct state-dependent management of ongoing threats to intertidal rocky reefs. Eleven participants, including management staff (decision makers and rangers) and intertidal marine ecologists were involved in a 1-day workshop to test the approach. Workshop participants were identified using snowball sampling (initial candidates are asked to recommend additional candidates from their professional network and participants are selected from this broader pool of candidates [Patton 2002]). Participants were selected if their expertise was directly relevant to the decision context (i.e., natural resource management, visitor management, or intertidal reef ecology). This research was approved by the Human Ethics Committee of the University of Melbourne (HREC Project Number: 1237358.1).

Conceptual models were constructed to represent the ecosystem dynamics of intertidal rocky reefs and key threatening processes (step 1) (Pocklington et al. 2012). A mat-forming brown alga, *Hormosira banksii*, was identified as a key ecological indicator that represented the overarching environmental objective of Victoria's MNPs "to maintain biodiversity." *H. banksii* provides important habitat for a diverse array of intertidal species and is particularly susceptible to trampling by visitors (a key threatening process) (Povey & Keough 1991; Keough & Quinn 1998). Participants engaged in a facilitated discussion to collectively define the temporal and spatial scale for management and management constraints (step 1).

An objectives hierarchy was used to elicit environmental, social, and economic objectives and performance measures (step 2). Workshop participants defined 4 discrete management alternatives that could be implemented within the management time horizon.

Ecological scenarios were developed for *H. banksii* based on the principles of scenario planning (step 3). The ecological scenarios developed represent the current state of *H. banksii* cover and 3 plausible future states of reduced cover of *H. banksii* cover due to increased threatening processes. The scenarios were developed prior to the workshop and were informed by long-term monitoring data, experimental research, and decision makers' expert judgment about undesirable condition of *H. banksii* on intertidal reefs.

We elicited participants' expert judgment on the effectiveness of management alternatives on all management objectives under each ecological scenario (step 4). Participants worked in groups to provide best guess, optimistic, and pessimistic consequence estimates, which were based on the assumption that management alternatives had been in place for 3 years. To provide these estimates, participants drew on their own expertise, scientific publications, and management agency reports. Because participants were working in groups and were time limited, they agreed a priori to provide optimistic and pessimistic consequence estimates to represent 90% credible bounds (reflecting a 3-point, rather than 4-point elicitation approach [Speirs-Bridge et al. 2010]). Two decision makers responsible for intertidal reef management provided their combined value judgments to weight objectives using the swing weighting technique, where the assigned weights represented the management agency's organizational priorities. A weighted additive model combined the consequence estimates and objective weights (Eqs. 1 and 2), which generated decision scores for each management alternative under each ecological scenario.

The pessimistic rule was used to interpret decision scores and select the best performing management alternatives under each ecological scenario (step 5). This provided the basis for setting a management threshold implementation range, which guided the decision on where to set the management threshold to manage the threat of trampling on *H. banksii.*

At the completion of the workshop all participants were asked to fill out a questionnaire consisting of 2 open ended questions that sought feedback on what aspects of the workshop participants thought did and did not work well.

Results

Step 1. Clarify the decision context

The workshop participants aimed to set management thresholds for *H. banksii* to enable state-dependent management of rocky intertidal reefs. Participants built on conceptual models and key ecological indicators developed by the management agency (Pocklington et al. 2012) to define the decision context. The spatial scale was restricted to a particular MNP, and the management time horizon was 15 years. The decision context involved balancing the environmental objective of maintaining the condition of *H. banksii* on intertidal reefs and the social objective was to encourage visitation to intertidal reefs, whilst ensuring that management intervention is cost-effective.

Step 2. Define management objectives and alternatives

Seven management objectives were defined; however, not all these objectives were independent. To avoid double counting, a subset of the original objectives was identified: maximize rocky intertidal reef communities, minimize resources spent on management, maximize visitor satisfaction, and maximize visitor numbers to the intertidal reef (Table 1). The fundamental objective to maximize rocky intertidal reef communities was represented by the proxy performance measure, *H. banksii* percent cover, and all other performance measures were direct measures of fundamental objectives.

Four discrete management alternatives were defined that represented technically feasible approaches to managing the threat of trampling on the intertidal reef over the next 15 years, including do nothing, status quo, medium protection, and high protection (Table 2).

Step 3. Develop ecological scenarios

The ecological scenarios developed were 70% cover, the current condition of *H. banksii* (calculated as a baseline population mean; Eq. 1, Supporting Information);

Table 1. Summary of management objectives defined by workshop participants that were relevant to setting management thresholds for *H. banksii* on rocky intertidal reefs.

Objective	*Indicator*	*Preference*	*Description*
Rocky intertidal reef communities	*H. banksii* (% cover)	Maximize	*H. banksii* is a proxy performance measure that represents the fundamental objective: maintenance of rocky intertidal reef invertebrate and algal communities. Increased cover of *H. banksii* represents increased diversity of intertidal invertebrates and algae occurring in the mid-shore of rocky intertidal reefs.
Resources	Australian $	Minimize	These include staff days (planning and on-the-ground staff days needed to manage the intertidal reef), infrastructure costs (e.g., building and maintaining park facilities), and educational costs (e.g., educational programs and production of information flyers).
Visitor satisfaction	Satisfaction index (%)	Maximize	Visitor satisfaction is a key performance indicator used by the management agency. All Victorian marine national parks were established in part for use and enjoyment by the public.
Visitor numbers	Thousands of people per year	Maximize	Visitation to all Victorian marine national parks is actively encouraged by the management agency.

Table 2. Summary of management alternatives defined by workshop participants that represented technically feasible approaches to managing the threat of trampling on the intertidal reef over the next 15 years.

Name	*Description*	*Total cost (AU$)*[a]
Do nothing	No direct management of the intertidal reef; incorporates minimal amount of staff days and budget required to maintain the existing infrastructure (e.g., signs, markers, and bins).	$10,500
Status quo	Current management approach (as of 2013): weekly ranger visits (increased during summer); user group management (e.g., licensed tour operators); management of educational programs; infrastructure maintenance.	$147,000
Medium protection	Doubling ranger time and tripling budget allocated to the intertidal reef: increased ranger visits; increased educational resources; increased infrastructure; partial reef closure during high temperature summer days; encouragement of use of neighboring intertidal reefs.	$282,600
High protection	Doubling ranger time and site hardening (e.g., installation of a stainless steel boardwalk) to restrict access to the intertidal reef and eliminate trampling.	$737,600

[a]*Total cost based on workshop participants' estimates of the number of staff days and budget required to implement management alternatives over 3 years.*

42% cover, the lower bound of variation of *H. banksii* (calculated as a lower 3 sigma control limit of a mean control chart; Eqs. 1–3, Supporting Information); 30% cover, a plausible decline in *H. banksii*, where recovery can take multiple years; 15% cover, an undesirable condition of *H. banksii*. Scenarios were developed with 9 years of monitoring data (Brown et al. 2013), experimental research (Povey & Keough 1991; Keough & Quinn 1998), and expert judgment.

Step 4. Estimate consequences and explore trade-offs

Participants worked in groups to provide a single set of best guess, optimistic, and pessimistic consequence estimates of management alternatives on objectives under each ecological scenario (with the nominated interval representing 90% credible bounds) (Table 3). Participants were more uncertain about the effectiveness of the intensive management alternatives on objectives,

Table 3. Estimated consequences[a] of the management alternatives on objectives under each ecological scenario elicited from workshop participants and normalized weights elicited from decision makers.

			Management alternative			
Objective	*scenario (% cover)*	*weight[b]*	*do nothing*	*status quo*	*medium protection*	*high protection*
Rocky intertidal reef communities	70	0.35	60 (45, 65)	70 (60, 75)	74 (62, 80)	80 (70, 85)
(average percentage cover of	42		27 (12, 35)	35 (20, 42)	50 (30, 55)	60 (40, 70)
H. banksii at the intertidal	30		20 (10, 30)	25 (15,35)	45 (25, 53)	55 (25, 65)
reef after 3 years of management)	15		2 (0, 5)	5 (0, 10)	20 (5, 30)	30 (10, 40)
Resources	70	0.18	10,500	147,000	282,600	737,600
(AU$ over 3 years of	42		"	"	"	"
management)	30		"	"	"	"
	15		"	"	"	"
Visitor satisfaction	70	0.30	55 (50, 60)	70 (60, 80)	70 (60, 80)	75 (50, 85)
(satisfaction index [%] after 3	42		50 (45, 55)	65 (55, 75)	65 (55, 75)	70 (45, 80)
years of management)	30		50 (45, 55)	65 (55, 75)	65 (55, 75)	70 (45, 80)
	15		50 (40, 55)	65 (50, 75)	65 (50, 75)	70 (40, 80)
Visitor numbers	70	0.18	500 (400, 550)	500 (400, 600)	500 (400, 600)	500 (400, 1000)
(thousands of people/year	42		500 (400, 550)	500 (400, 600)	500 (400, 600)	500 (400, 1000)
after 3 years of	30		500 (400, 550)	500 (400, 600)	500 (400, 600)	500 (400, 1000)
management)	15		450 (350, 500)	450 (350, 550)	450 (350, 550)	450 (350, 950)

[a] *Consequence estimates include the best guess and the 90% credible bounds in parentheses: (pessimistic estimate, optimistic estimate).*
[b] *Weights are normalized (0,1) and are based on the initial weights (0,100) specified by decision makers.*

which resulted in wider uncertainty bounds (see credible bound estimates in Table 3). Two decision makers provided weights for each objective representing the management agency's priorities (Table 3).

Step 5. Explore uncertainty and risk tolerance and set management thresholds

Consequence estimates and objective weights were combined using the weighted additive model (Eqs. 1 and 2) to calculate decision scores for each management alternative under each ecological scenario (Fig. 2). The decision scores reflect the substantial uncertainty of participants' consequence estimates for some management alternatives (Table 3; Fig. 2).

Following the pessimistic rule, a decision maker would select the following best performing management alternatives under each ecological scenario: status quo under the 70% cover scenario; medium protection under the 42% and 30% cover scenarios; and status quo under the 15% cover scenario.

Two exploratory checks were conducted of the model outputs interpreted using the pessimistic rule (Supporting Information): a breakdown of decision scores and one-dimensional sensitivity analysis. These checks illustrated the variable influence of most objectives (except for visitor numbers) on the final decision scores under the ecological scenarios (Supporting Information). The model outputs were sensitive to changing weights for 2 objectives (rocky intertidal reef communities and resources [Supporting Information]). These exploratory checks can prompt re-defining or re-estimating model parameters in steps 2 and 4; however, this was not deemed necessary in this case study.

Following the selection of the best performing management alternatives under each ecological scenario using the pessimistic rule, the decision maker set a management threshold implementation range for medium protection at 15–42% cover of *H. banksii* (Fig. 3). A risk-averse decision maker may err on side of caution and set the medium protection management threshold at 42% cover of *H. banksii*.

Step 6. Evaluate long-term monitoring data using management thresholds

Following management threshold selection, future monitoring data should be regularly assessed against the 42% cover medium protection management threshold. If the management threshold is breached, then the medium protection management approach should be implemented.

Discussion

Setting management thresholds remains a challenging task in conservation (Bennetts et al. 2007; Lindenmayer et al. 2013). This novel participatory modeling approach provides an accessible and effective method to set conservation management thresholds. It allows for competing objectives, the incorporation of scientific

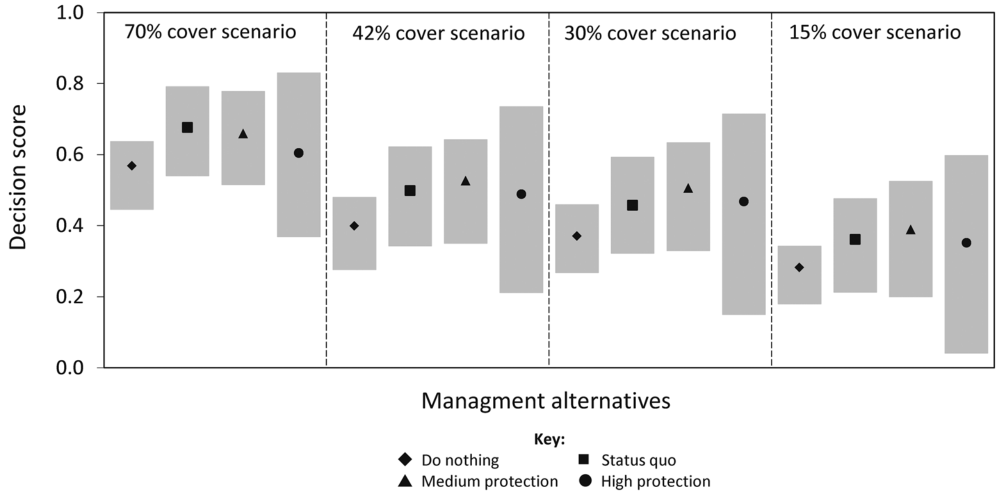

Figure 2. The performance of the 4 management alternatives under the ecological scenarios representing the current condition (70% cover) and 3 plausible states of reduced cover of H. banksii *(42%, 30%, and 15% cover). Decision scores were calculated using participants' consequence estimates and objective weights derived in step 4 of the process. The nominal decision score (based on the participants' best guess estimates) is shown as a symbol for each management alternative, and the bars show the range in decision scores, from the lower bound decision score (based on the participants' pessimistic estimates) to the upper bound decision score (based on the participants' optimistic estimates).*

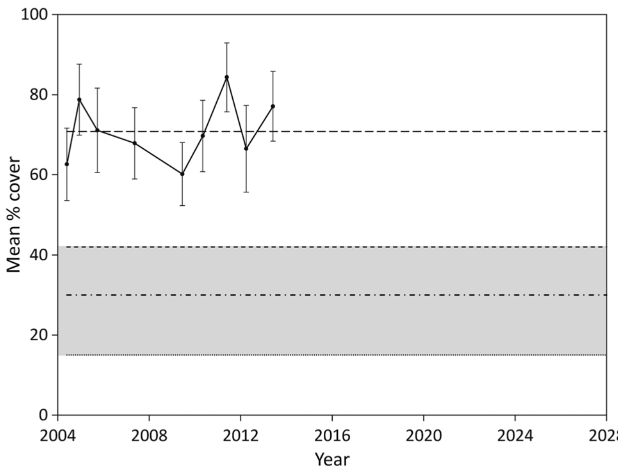

Figure 3. The medium protection management threshold implementation range (gray shading) for H. banksii*, informed by the pessimistic rule (i.e., based on the best performing lower bound decision score for the management alternatives under each ecological scenario; Fig. 2). Areas with no shading indicate where to continue the status quo management alternative. The current condition of* H. banksii *(solid black line, mean percent cover [SE]) at the intertidal reef is shown from 2004 to 2013, and the ecological scenarios are represented by the 4 horizontal lines (long-dashed line, 70% cover scenario; dashed line, 42% cover scenario; dashed and dotted line, 30% cover scenario; dotted line, 15% cover scenario).*

understanding, and value judgments about the management of the ecosystem and does not require participants to have in-depth quantitative modeling skills. This approach assisted in setting management thresholds for *H. banksii,* a key ecological indicator, so that the ongoing threat of trampling on the intertidal reef could be managed. The multiple competing objectives of this case study (Table 1) reflect increasingly considered environmental, social, and economic components of conservation decisions (e.g., Martin et al. 2011; Runge 2011).

The novelty of this approach lies in the unique combination of techniques used to set management thresholds. The management threshold determined through this approach encapsulated empirical evidence, participants' scientific knowledge, and value judgments. Empirical evidence includes research or monitoring results, and participants' scientific knowledge represents their interpretation of cause-and-effect relationships within ecosystems, whereas values represent individual or organizational priorities (Keeney 1992; Failing et al. 2007). These sources of information are valued by conservation decision makers (Cook et al. 2012) and highlight that conservation decision making is not a value-free process (Failing et al. 2007).

The ecological scenarios developed in step 3 are a key feature of this approach; they provide the foundation for where to set management thresholds. In step 4, participants estimate the consequences of management alternatives on management objectives under each ecological scenario. In step 5, decision makers select the preferred management alternative under each ecological scenario and use this information to set a management threshold implementation range for the preferred management alternatives. This range is used by decision makers to set management thresholds. We recommend scenario planning as a technique to assist participants in developing ecological scenarios that represent plausible future states of the key ecological indicator. Scenario planning has a long history of use in business strategic planning and has been advocated over the last decade to support conservation decisions (Peterson et al. 2003; Game et al. 2013). It is particularly useful in facilitating the creative exploration of complex natural systems, the uncertainty of future trajectories of these systems, and the development of management alternatives to address future unfavorable states.

The most positively reported aspect of the workshop was that it was well-organized and facilitated (75% of participants [Supporting Information]). Well facilitated participatory modeling approaches can improve communication and build trust between scientists and decision makers (Addison et al. 2013). Part of the success of the workshop came from using the participatory modeling approach that did not require in-depth quantitative modeling skills. Widely accessible spreadsheet software was used to construct the weighted additive model, and model outputs were created during the workshop and viewed immediately by participants (e.g., Fig. 2). Thus, this approach is accessible to management agencies and participants with limited modeling expertise.

Our approach was not without some challenges; in particular participants can be subject to a substantial elicitation burden when involved in participatory modeling approaches (Speirs-Bridge et al. 2010). Sixty-three percent of participants found the elicitation of quantitative consequence estimates under each ecological scenario particularly challenging (Supporting Information). Participants believed there was a lack of opportunity to document the assumptions and rationale behind the estimates effectively. Some also thought unqualified to provide quantitative estimates and noted a desire to revisit the quantitative modeling stage. These limitations can be overcome by documenting participants' assumptions to reveal differences in perspectives; documenting supporting information so that consequence estimates can be re-visited and updated with new scientific knowledge when available; or using rapid prototyping to increase participants' familiarity with the modeling process and to refine, improve, or expand modeling steps as necessary (Blomquist et al. 2010).

Uncertainty is an important component to consider in any decision (Burgman 2005; Regan et al. 2005), and explicit consideration of uncertainty is encouraged throughout this participatory modeling approach. First, ecological scenarios, the foundation for setting management thresholds, are developed to represent uncertainty associated with the future trajectories of ecological systems. Second, the outputs of the weighted additive model carry through the uncertainty associated with participants' consequence estimates, which reflected participants' best guess and 90% credible bounds (Fig. 2). This is unlike other approaches, such as stochastic dynamic programming, which provide only an optimal solution to setting management thresholds without considering uncertainty (e.g., Martin et al. 2009). Third, management threshold implementation ranges are set in the face of uncertainty with one of three decision rules in step 5. For example, a decision maker may take a precautionary approach and use the pessimistic rule to set a management threshold implementation range for 15–42% cover of *H. banksii* for the medium protection alternative (Fig. 3). Where a management threshold will be set within the management threshold implementation range reflects a decision makers' risk tolerance associated with the decision context. Just like the need for transparently incorporating uncertainty, decision makers' should openly state their appetite for risk in conservation decision making (Burgman 2005; Regan et al. 2005). In our case study, we illustrated how a risk-averse decision maker may err on side of caution and set the medium protection management threshold at 42% cover of *H. banksii*.

If the preferred management alternative is not apparent due to uncertainty, there are several techniques to help clarify uncertainty that can be incorporated into the modeling approach. Sensitivity analysis can be used to highlight whether any model parameters need to be re-defined or re-estimated (demonstrated in Supporting Information). Expected value of perfect information analysis can be used to assess the benefits of clarifying uncertainty before investing in potentially expensive data gathering exercises (e.g., Runge et al. 2011; Moore & Runge 2012). If warranted, investment in additional research can complement expert judgment and experimental adaptive management could be used to trial management alternatives and determine their effectiveness (Walters & Holling 1990).

The feedback loops of this approach highlight the recurrent nature of state-dependent management and encourage revisiting modeling steps where necessary (Fig. 1). The review feedback loop provides an opportunity to clarify uncertainty associated with model parameters and revise the decision context where necessary. The learn feedback loop ensures that the effectiveness of management actions is assessed using empirical evidence and if necessary modifications are made to the management thresholds to ensure future management is more effective. This type of knowledge updating is considered passive, compared with experimental adaptive management (Walters & Holling 1990; Runge 2011); nevertheless, it is vital to ensure the on-going effectiveness of state-based management.

This participatory modeling approach encourages a proactive form of conservation management, where management thresholds and associated management actions are defined a priori for ecological indictors, rather than reacting to unexpected future ecosystem changes. Future budgets and organizational priorities may prevent implementing a particular management action, but at a minimum, breaching a management threshold will trigger a more informed investigation to determine what new management strategies are obtainable.

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Supporting Information

Information on monitoring data used to develop the ecological scenarios (Appendix S1), exploratory checks of model outputs (Appendix S2), and workshop feedback from participants (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited

Addison PFE, Rumpff L, Bau SS, Carey JM, Chee YE, Jarrad FC, McBride MF, Burgman MA. 2013. Practical solutions for making models indispensable in conservation decision-making. Diversity and Distributions **19:**490–502.

ANZECC. 2000. National water quality management strategy. No. 7a. Australian guidelines for water quality monitoring and reporting. Australian and New Zealand Environment and Conservation Council/Agriculture and Resource Management Council of Australia and New Zealand. Australian Government Publishing Service, Canberra.

Belton V, Stewart TJ. 2002. Multiple criteria decision analysis: an integrated approach. Kluwer, Boston, Massachusetts.

Bennetts RE, Gross JE, Cahill K, McIntyre C, Bingham BB, Hubbard A, Cameron L, Carter SL. 2007. Linking monitoring to management and planning: Assessment points as a generalized approach. The George Wright Forum **24:**59–77.

Biggs D, Abel N, Knight AT, Langston A, Ban NC. 2011. The implementation crisis in conservation planning: Could "mental models" help? Conservation Letters **4:**169–183.

Biggs HC, Rogers KH. 2003. An adaptive system to link science, monitoring and management in practice. Pages 59–80 in du Toit JT, Biggs H, Rogers KH, editors. The Kruger experience: ecology and management of savanna heterogeneity. Island Press, Washington, D.C.

Blomquist SM, Johnson TD, Smith DR, Call GP, Miller BN, Thurman WM, McFadden JE, Parkin MJ, Boomer GS. 2010. Structured decision-making and rapid prototyping to plan a management response to an invasive species. Journal of Fish and Wildlife Management **1:**19–32.

Brown H, Donnelly D, Woods B, Edmunds M. 2013. Intertidal reef monitoring program: Central Victoria marine protected areas, July 2013. Parks Victoria Technical Series No. 95. Parks Victoria, Melbourne.

Burgman MA. 2005. Risks and decisions for conservation and environmental management. Cambridge University Press, Cambridge, United Kingdom.

Chankong V, Yacov YY. 1983. Multiobjective decision making: theory and methodology. Dover Publications, Mineola, New York.

Clemen RT. 1996. Making hard decisions: an introduction to decision analysis. Duxbury Press, Pacific Grove, California.

Cook CN, Carter R, Fuller RA, Hockings M. 2012. Managers consider multiple lines of evidence important for biodiversity management decisions. Journal of Environmental Management **113:**341–346.

Failing L, Gregory R, Harstone M. 2007. Integrating science and local knowledge in environmental risk management: a decision-focused approach. Ecological Economics **64:**47–60.

Field SA, Tyre AJ, Jonzen N, Rhodes JR, Possingham HP. 2004. Minimizing the cost of environmental management decisions by optimizing statistical thresholds. Ecology Letters **7:**669–675.

Game E, Meijaard E, Sheil D, McDonald-Madden E. 2013. Conservation in a wicked complex world: Challenges and solutions. Conservation Letters **7:**271–277.

Gregory R, Failing L, Harstone M, Long G, McDaniels T, Ohlson D. 2012. Structured decision making: a practical guide to environmental management choices. John Wiley & Sons, Chichester, United Kingdom.

Groffman P, et al. 2006. Ecological thresholds: The key to successful environmental management or an important concept with no practical application? Ecosystems **9:**1–13.

Keeney RL. 1992. Value-focused thinking: a path to creative decision-making. Harvard University Press, Cambridge, Massachusetts.

Keough MJ, Quinn GP. 1998. Effects of periodic disturbances from trampling on rocky intertidal algal beds. Ecological Applications **8:**141–161.

Lindenmayer DB, Piggott MP, Wintle BA. 2013. Counting the books while the library burns: Why conservation monitoring programs need a plan for action. Frontiers in Ecology and the Environment **11:**549–555.

Lyons JE, Runge MC, Laskowski HP, Kendall WL. 2008. Monitoring in the context of structured decision-making and adaptive management. Journal of Wildlife Management **72:**1683–1692.

Martin J, Fackler PL, Nichols JD, Runge MC, McIntyre CL, Lubow BL, McCluskie MC, Schmutz JA. 2011. An adaptive management framework for optimal control of hiking near golden eagle nests in Denali National Park. Conservation Biology **25:**316–323.

Martin J, Runge MC, Nichols JD, Lubow BC, Kendall WL. 2009. Structured decision making as a conceptual framework to identify thresholds for conservation and management. Ecological Applications **19:**1079–1090.

Moore JL, Runge MC. 2012. Combining structured decision making and value of information analysis to identify robust management strategies. Conservation Biology **26:**810–820.

Morrison L. 2008. The use of control charts to interpret environmental monitoring data. Natural Areas Journal **28:**66–73.

Nichols JD, Runge MC, Johnson FA, Williams BK. 2007. Adaptive harvest management of North American waterfowl populations: A brief history and future prospects. Journal of Ornithology **148:**343–349.

Nichols JD, Williams BK. 2006. Monitoring for conservation. Trends in Ecology & Evolution **21:**668–673.

Patton MQ. 2002. Qualitative evaluation and research methods. Sage Publications, Newbury Park, California.

Peterson GD, Cumming GS, Carpenter SR. 2003. Scenario planning: A tool for conservation in an uncertain world. Conservation Biology **17:**358–366.

Pocklington JB, Carey JM, Murshed MDT, Howe SAJ. 2012. Conceptual models for Victorian ecosystems: marine and estuarine ecosystems. Technical series 66. Parks Victoria. Parks Victoria, Melbourne.

Povey A, Keough MJ. 1991. Effects of trampling on plant and animal populations on rocky shores. Oikos **61:**355–368.

Regan HM, Ben-Haim Y, Langford B, Wilson WG, Lundberg P, Andelman SJ, Burgman MA. 2005. Robust decision-making under severe uncertainty for conservation management. Ecological Applications **15:**1471–1477.

Runge MC. 2011. An introduction to adaptive management for threatened and endangered species. Journal of Fish and Wildlife Management **2:**220–233.

Runge MC, Converse SJ, Lyons JE. 2011. Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. Biological Conservation **144:**1214–1223.

Runge MC, Walshe T. 2014. Identifying objectives and alternative actions to frame a decision problem. Pages 29–43 in Guntenspergen GR, editor. Application of threshold concepts in natural resource decision making. Springer, New York.

Sandker M, Campbell BM, Ruiz-Perez M, Sayer JA, Cowling R, Kassa H, Knight AT. 2010. The role of participatory modeling in landscape approaches to reconcile conservation and development. Ecology and Society **15:**http://www.ecologyandsociety.org/vol15/iss12/art13/.

Schoemaker PJ. 1995. Scenario planning: A tool for strategic thinking. Sloan Management Review **36:**25–25.

Speirs-Bridge A, Fidler F, McBride M, Flander L, Cumming G, Burgman M. 2010. Reducing overconfidence in the interval judgments of experts. Risk Analysis **30:**512–523.

von Winterfeldt D, Edwards W. 1986. Decision analysis and behavioral research. Cambridge University Press, Cambridge, United Kingdom.

Walters CJ, Holling CS. 1990. Large-scale management experiments and learning by doing. Ecology **71:**2060–2068.