

Title: Integrating decision triggers into conservation management practice

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Abstract

1. Decision triggers show great potential for facilitating timely management action, promoting evidence-based management and preventing undesirable changes to the status of species, ecosystems and threats. Integration of decision triggers into day-to-day management practice has been slow, constrained by insufficient resources and limited in-house expertise. Arguably, the greatest impediment is the lack of an overarching process with robust and accessible methods for developing and implementing decision triggers in a manner that fits within an organisation's current processes and skill sets.
2. We identify the steps necessary for setting decision triggers and highlight how these steps align with commonly used conservation planning and management frameworks, for ease of adoption.
3. We emphasise that decision triggers do not require a known ecological threshold, and can be applied to data rich and data poor contexts, with single or multiple management objectives.
4. *Synthesis and applications.* This work highlights the necessary steps involved, and importantly, the suite of methods that can be used to set decision triggers with the aim to support practitioners in the development of robust and defensible decision triggers.

Keywords: environment; evidence-based management; decision-making; proactive management; monitoring; thresholds, adaptive management; decision triggers, conservation planning, management practices

Introduction

Successful conservation outcomes are reliant on effective, timely and well-informed management. To achieve this, conservation and natural resource managers need to be armed with decision support tools that utilize the best available information. Recent decades have seen considerable progress in the global application of evidence-based practices in conservation management, encompassing a variety of approaches to support effective management decisions (Table 1). Many management organisations have made progress towards implementing elements of these frameworks to promote evidence-based management (e.g., adaptive management and management effectiveness evaluation; Table 1). However, challenges still exist in applying these approaches to real world problems, such that species declines have been observed without management action being initiated (Martin *et al.* 2012) or reactionary management decisions are made only after significant ecological degradation has occurred (Lindenmayer, Piggott & Wintle 2013).

The use of thresholds or triggers for action has been suggested as a mechanism to formally incorporate monitoring data into management decisions (e.g., Connors & Cooper 2014) and there is support from both researchers and practitioners for the use of decision triggers in the management of natural systems (Addison, Cook & de Bie 2016; Cook *et al.* 2016). South Africa uses thresholds in management practice (thresholds of potential concern; Biggs & Rogers 2003) and several countries are shifting towards the adoption of triggers based approaches (e.g., United States (Martin *et al.* 2011); Canada (Timko & Innes 2009); Australia (Addison, de Bie & Rumpff 2015); New Zealand (Addison, Cook & de Bie 2016)). While methods and concepts that inform when to intervene in natural systems have been described in many ways (see Cook *et al.* 2016), we use the term decision triggers, defined as a point or zone in the status of an ecological attribute (e.g., species, ecosystem or threat) that when crossed triggers a management intervention (Cook *et al.* 2016). Importantly, our definition distinguishes decision triggers from approaches that require the identification of an ecological threshold (e.g., the point of rapid or irreversible ecological change in a system; Groffman *et al.*, 2006), broadening the application to a variety of management contexts. Decision triggers can be informed by

ecological thresholds or bounds of natural variability, where these are known (e.g., Biggs & Rogers 2003), but can also enable proactive management for a broader suite of contexts (Cook *et al.* 2016). Our definition also allows decision triggers to capture the economic, social, environmental and political dimensions, and complex trade-offs, that drive management (Adger *et al.* 2003; Addison, de Bie & Rumpff 2015).

While conservation practitioners have expressed support for the idea of decision triggers to guide management (Addison, Cook & de Bie 2016), setting meaningful decision triggers for management remains a daunting task (Groffman *et al.* 2006). Agencies lack processes and methods to develop decision triggers in-house, and have emphasised the need for approaches to fit within existing evidence-based frameworks and operational constraints (Addison, Cook & de Bie 2016). Methods for integrating a form of trigger do exist for some management contexts, and have contributed valuable conceptual and methodological advances (Biggs *et al.* 2011b). However, these methods are often based on the presence of ecological thresholds, require significant ecological understanding, monitoring data, and modelling expertise (e.g., Martin *et al.* 2009; Scholes & Kruger 2011). In addition, there has been no synthesis of the variety of methods that exist that documents the different applications of decision triggers to support conservation management.

Drawing on the depth of existing management, evaluation and conservation planning frameworks designed to promote adaptive decision-making processes (Schwartz *et al.* 2017), we highlight the critical stages to integrate evidence in decision-making, and where development and implementation of decision triggers fits (Fig. 1, Table 1). Importantly, we also identify a range of methods for setting decision triggers (Tables 2 & 3) that are suitable for different management contexts, including both data rich and data poor environments and those with single versus multiple (potentially competing) management objectives. If decision triggers can be integrated into existing frameworks, this will fill a critical gap in evidence-based conservation (Cook *et al.* 2016), helping close the loop between monitoring and management action.

Fitting decision triggers into management frameworks

The development and effective integration of decision triggers relies on a robust process for decision-making, including steps for setting a decision context, identifying objectives and indicators, determining management actions, and conducting monitoring and evaluation (Biggs & Rogers 2003; Martin *et al.* 2009; Addison, de Bie & Rumpff 2015) (Fig. 1). Many of these steps exist in several conservation management frameworks (Table 1). Here we outline the critical elements of these steps as they relate to setting decision triggers, and the range of tools that can assist to achieve these steps (Table 2 & 3).

Defining the decision context is a crucial first step in environmental management decision-making (Gregory *et al.* 2012). It involves clearly articulating and defining the scope of management, forming the basis for subsequent decision-making. This is pertinent to decision triggers, as a basic knowledge of important processes (e.g., biotic and abiotic interactions) and key drivers (e.g. natural and anthropogenic processes) is required. Literature reviews and local ecological knowledge can assist in developing and documenting the current conceptual understanding of a system (Fazey *et al.* 2006). Conceptual models can be produced by drawing on peer-reviewed or grey literature (e.g., threatened species recovery plans) and/or by eliciting knowledge using tools such as mental models (Biggs *et al.* 2011a), ideally using a wide range of stakeholders/participants from diverse backgrounds (Gregory *et al.* 2012). A time horizon (e.g., management planning cycle) and spatial extent of management should also be clearly defined (e.g., discrete spatial unit, such as a single protected area, or species' range). This will inform the development of management objectives, actions and monitoring.

Management objectives can be taken directly from existing documentation, such as management plans and strategies. If not available, spending time developing specific, robust and measurable management objectives is crucial (Gregory *et al.* 2012). There are many methods that can assist with setting robust and measurable objectives, such as value-focused thinking and objectives hierarchies (Gregory *et al.* 2012).

Each management objective requires at least one indicator, which represents the attribute of interest (e.g., species, ecosystem or threat) for which the decision trigger will be set. Here we define indicators as a measurable representation of the stated objectives (Dale & Beyeler 2001). Indicators should show a quantifiable and measurable relationship to the desired system state. In a species context, indicators could include population size, percentage cover or fecundity rates (Dale & Beyeler 2001). For ecosystem based contexts, indicators could be diversity indices or aggregate indicators, such as vegetation condition (Gibbons *et al.* 2009) or biometric assessments (Feld *et al.* 2010). For threats, indicators can measure the threat directly (e.g., population size of an invasive species), or measure environmental variable(s) that are known system drivers (e.g., levels of precipitation associated with reproductive events). Proxy measures may be most appropriate and efficient when the system dynamics and subsequent relationships between variables is well established (e.g., using models). There is a wealth of practical guidance for selecting appropriate indicators and their unit of measure, including conceptual frameworks, such as the Driver-Pressure-State-Impact-Response framework (Mace & Baillie 2010), and computational approaches, such as state-and-transition models (Rumpff *et al.* 2011) and qualitative loop models (Hayes *et al.* 2015).

To develop decision triggers, the bounds within which management aims to maintain an attribute (desirable and undesirable states of the system) must be defined. The desired state or condition of the system should reflect what a management organisation aspires to achieve and maintain over time. Indicator condition can be defined by using baseline information, such as bounds of natural variability displayed in monitoring data (Landres, Morgan & Swanson 1999), or identified through additional monitoring or research (Woodley 2010). The desired state may also be defined according to environmental targets set within regulatory or policy requirements, which may reflect value-based judgements (Nie & Schultz 2012). Defining the desired state of the system acts to identify the zones which form the foundation for setting decision triggers, which if breached prompt specific action(s).

The *a priori* consideration of potentially effective management actions separates decision triggers from other threshold concepts that relate to a single, predefined management response. If available management actions cannot affect the state of the system (due to either a lack of ecological

understanding, political will or sufficient budget), decision triggers may not be appropriate until such actions are identified (e.g., through further research), or political or organisational support increases. To guard against a situation where managers are anchored in the *status quo* of commonly used actions, or are unaware of all of the management actions available (Runge & Walsh 2014), it is important to think creatively about the full suite of management actions that could be implemented. Systematic reviews (Pullin & Stewart 2006), evidence summaries (Dicks, Walsh & Sutherland 2014), and strategic foresight approaches (Cook *et al.* 2014) can be particularly useful in identifying a range of possible interventions and their efficacy. However, in reality the set of available management actions is often small, due to the limited set of variables that managers are able to influence (Worboys *et al.* 2015). Therefore, the choice of management actions may be relatively straightforward and able to be made based on the available management experience.

Setting decision triggers

Decision triggers can be set using a number of methods, depending on the availability of scientific data and expertise, the number of objectives for management and the resources available. The appropriate methods will depend on whether decision triggers are to be set for single or multi-objective decisions (see computational methods), or whether decision triggers will be set using value-based information only. Within the diversity of approaches are options that can be used in data rich situations (i.e., where there is a robust evidence base) as well as the more common data poor situations (Table 2). It should be noted that when a range of feasible management actions are available to manage the system, it is possible to set multiple trigger points across the spectrum of desirable to undesirable system states that explicitly factor in management response time and represent different levels of management intensity (from proactive to reactive management). Proactive decision points represent early warning points, such as a small shift from the acceptable condition of an indicator, which may trigger precautionary actions, increased monitoring or further investigation of the cause of

the shift. A reactive trigger point represents a move into unacceptable condition of an indicator, which if breached requires urgent and remedial action.

Computational methods – for single objective contexts

When research is available that provides a good understanding of the system, and there is relatively long-term monitoring data (e.g., more than 5 years of annual census data) for indicators, then computational methods can be used to set decision triggers (Tables 2 & 3). Where there is a single objective for the system (e.g., one environmental objective that is managed and monitored, in the absence of any competing environmental, social, political or economic objectives), statistical approaches can be used to derive the bounds of acceptable and unacceptable system states and associated trigger points for action. These approaches are also applicable to systems with multiple (independent) indicators if the indicators are evaluated. Some statistical methods for setting decision triggers in single objective systems include control charts (Morrison 2008), statistical thresholds (Field *et al.* 2004), fisheries decision criteria (Link 2005), or thresholds of potential concern (Scholes & Kruger 2011). These methods are generally focused on determining the statistical bounds of natural variation (e.g., 3 standard deviations from the mean) or calculated from the variability displayed in baseline data (e.g., control charts; Morrison 2008) (Table 3). Using the natural variability in an indicator to set quantitative upper and lower bounds on desired condition of the ecological attribute provides unambiguous trigger points for action.

Statistical methods for setting multiple trigger points can add a precautionary buffer into the trigger for action (e.g., thresholds of potential concern; Scholes & Kruger 2011) and be used to account for uncertainty in monitoring data (e.g., Link 2005; Morrison 2008), and the level of resources required for the intervention (Cook *et al.* 2016). Similarly, statistical methods can account for the implications of Type I and II error rates (e.g., using ROC curves; Connors & Cooper 2014). In the context of decision triggers, a Type I error rate represents the chance that a trigger is breached when no true change has occurred in the population represented by the indicator. A Type II error rate represents the chance that a decision trigger is not breached despite a true change occurring in the population

represented by the indicator. The environmental consequences associated with statistical inference are therefore a crucial consideration when setting robust and informed decision triggers using statistical methods (Field *et al.* 2004).

When monitoring data are limited, as is commonly the case in management organisations, it may be possible to set preliminary decision triggers. Statistical methods that can be used with minimal data include ‘self-starting’ control charts (Pazhayamadam *et al.* 2013) and bootstrapping approaches that re-sample from the existing data (Anderson & Thompson 2004). Both of these approaches allow for preliminary decision triggers to be set, which can be monitored, evaluated and updated as new data become available (Table 3).

Computational methods – for multiple objective contexts

In situations where there are multiple competing objectives (e.g., social, economic, political and environmental) that must be considered when setting decision triggers, it may be more appropriate to use predictive methods, which explicitly deal with potential trade-offs among objectives, to set trigger points. Some predictive methods use advanced computational models, such as optimization techniques to model ecosystem behavior with environmental, economic or social constraints (Martin *et al.* 2009), whilst other approaches utilize expert judgement to make predictions of the effectiveness of alternative management actions based on the state of an indicator, such as multi-objective participatory modelling (Addison, de Bie & Rumpff 2015). These methods assist with setting decision triggers for indicators in the face of competing objectives. For example, protecting biodiversity might need to be balanced with competing social and economic objectives: increasing visitation to a national park, and minimizing the resources spent on management interventions (Addison, de Bie & Rumpff 2015). In this example, the value judgement is that national parks are for people not just for biodiversity. These values-based objectives are integrated with monitoring data and other environmental knowledge (e.g., data on ecological thresholds, system drivers and the current condition of indicators), and decision-makers must make explicit judgements about the relative importance (preference or priority) of the competing objectives.

Predictive methods for helping set decision triggers in multi-objective contexts often have more flexible data requirements than statistical methods for single objective contexts. This is because when empirical evidence is lacking, predictive modelling approaches can be used (e.g., stochastic dynamic programming for predicting ecosystems responses to management actions; Martin *et al.* 2009), incorporating or replaced by expert judgement (e.g., structured expert judgment about the likely ecological responses to management actions; Addison, de Bie & Rumpff 2015). However, these methods still require conceptual models of the system, and background scientific evidence to inform how the models are structured (Tables 2 &3).

Value-based approaches

Social, economic and political factors often play a critical role in managed systems (Adger *et al.* 2003), and decision triggers can be based entirely on values or preferences (Addison, de Bie & Rumpff 2015). This type of trigger could represent an environmental objective heavily influenced by social preferences, such as maintaining a population of a flagship species at a level that will attract visitors to a protected area (Martin *et al.* 2011). Setting decision triggers using value-based information means that decision triggers will often represent arbitrary levels that make no reference to the ecology of the system, but instead represent socially unacceptable condition or the level of an indicator that regulators, decision-makers, or society wish to avoid or that are mandated under legislative or management authorities (Tables 2 & 3).

Implementing decision triggers

For decision triggers to be effective there must be a commitment to ongoing monitoring of the relevant indicators. Monitoring should be targeted (i.e., using an indicator where the relationship to the system of interest is clearly defined), cost-effective, and well-designed (e.g., balancing Type I and II error rates), to generate the information needed to make decisions. Where decision triggers are developed using a pre-existing monitoring schedule it is essential to determine if the current design of the monitoring program is sufficiently sensitive to detect change at the appropriate spatial and temporal

scales to determine when a trigger is breached. Careful consideration should be given to whether the frequency of monitoring will enable time to react when a trigger is breached. This requires an understanding of the rate of change in the system, the capacity of management to alter the state of the system, and how quickly the management actions could influence the state of the system. Once active, monitoring data should be regularly evaluated for trigger breaches.

The use of decision triggers should be an adaptive process, with iterative cycles of review, commonly found in adaptive management frameworks. As understanding of the system increases and the ecological attribute of interest responds to changing environmental conditions and management regimes, it may be necessary to refine the conceptual model of system dynamics, the most appropriate indicator or the appropriate management actions. The timeline for the review of the process can be tailored to align with the larger management cycles of an organisation, such as management plan review (e.g. 1-2 years) or reporting cycles (e.g., 3-5 years).

The success of decision triggers hinges on management action being taken when the monitoring data indicates it is warranted. If a trigger was breached then a review should be conducted including: (1) whether the identified management action was taken, and (2) whether it had the desired result on the condition of the indicator. If a trigger was breached and action was not taken then a review should determine why (e.g., insufficient funding or change in political/organisational situation). If the management action did not have the desired result on the indicator, then the suitability of the management action should be re-evaluated and refined. If a trigger was not breached, then an evaluation should focus on identifying and incorporating new information on system dynamics that consider whether a change to an indicator, trigger point or management action are required. Ultimately, each review should end with ensuring that there is a commitment to ongoing monitoring and the use of decision triggers to guide management.

Conclusions

Decision triggers will not be relevant in all management contexts. They require high-level commitment to the process, along with a willingness to conduct ongoing monitoring and undertake active management. We acknowledge conservation management operates within variable political environments and budgets that can constrain conservation efforts, so there will be occasions where decision triggers cannot or should not be implemented. In the context where decision triggers are relevant, we outline a process and flexible suite of approaches to developing and implementing decision triggers, which capture a wide range of management contexts, and demonstrate how these align with frameworks already in place. We believe that decision triggers can fill an important gap, linking monitoring data to management action and improving in evidence-based conservation, and that the steps and methods we outline can contribute to the wider adoption of decision triggers by conservation practitioners. The next steps are to test a wide range of case studies to illustrate the application of decision triggers to real world management problems, to provide a compendium of diverse applications for conservation practitioners to learn from and build upon.

Authors' contributions

KdB, PA and CC contributed equally to the project conception and development of the decision triggers process. KdB led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Data accessibility

Data has not been achieved as the manuscript does not use data.

305 References

- 306 Addison, P.F.E., de Bie, K. & Rumpff, L. (2015) Setting conservation management thresholds using a
 307 novel participatory modeling approach. , **29**, 1411–1422.
- 308 Addison, P.F.E., Cook, C.N. & de Bie, K. (2016) Conservation practitioners' perspectives on decision
 309 triggers for evidence-based management. *Journal of Applied Ecology*, **53**, 1351–1357.
- 310 Adger, W.N., Brown, K., Fairbrass, J., Jordan, A., Paavola, J., Rosendo, S. & Seyfang, G. (2003)
 311 Governance for sustainability : towards a 'thick' analysis of environmental decisionmaking.
 312 *Environment and Planning A*, **35**, 1095–1110.
- 313 Anderson, M.J. & Thompson, A.A. (2004) Multivariate control charts for ecological and
 314 environmental monitoring. *Ecological Applications*, **14**, 1921–1935.
- 315 ANZECC. (2000) *Australian Guidelines for Water Quality Monitoring and Reporting*. Australian
 316 Government, Canberra.
- 317 Biggs, D., Abel, N., Knight, A.T., Leitch, A., Langston, A. & Ban, N.C. (2011a) The implementation
 318 crisis in conservation planning : could 'mental models' help? *Conservation Letters*, **4**, 169–183.
- 319 Biggs, H., Ferreira, S., Freitag-Ronaldson, S. & Grant-Biggs, R. (2011b) Taking stock after a decade:
 320 Does the 'thresholds of potential concern' concept need a socio-ecological revamp? *Koedoe*, **53**.
- 321 Biggs, H.C. & Rogers, K.M. (2003) An adaptive system to link science, monitoring and management
 322 in practice. *The Kruger experience: Ecology and Management of Savanna Heterogeneity* (eds
 323 J.T. du Toit, K. Rogers, & H.C. Biggs), pp. 59–80. Island Press, Washington.
- 324 Connors, B.M. & Cooper, A.B. (2014) Determining Decision Thresholds and Evaluating Indicators
 325 when Conservation Status is Measured as a Continuum. *Conservation Biology*, **28**, 1626–1635.
- 326 Conservation Measures Partnerships. (2007) *Conservation Measures Partnerships Open Standards for
 327 the Practice of Conservation, Version 2.0*. Report.
- 328 Cook, C.N., de Bie, K., Keith, D.A. & Addison, P.F.E. (2016) Decision triggers are a critical part of
 329 evidence-based conservation. *BIOC*, **195**, 46–51.
- 330 Cook, C.N., Wintle, B.C., Aldrich, S.C. & Wintle, B.A. (2014) Using Strategic Foresight to Assess
 331 Conservation Opportunity. *Conservation Biology*, **28**, 1474–1483.
- 332 Dale, V.H. & Beyeler, S.C. (2001) Challengers in the development and use of ecological indicators.
 333 *Ecological Indicators*, **1**, 3–10.
- 334 Dicks, L. V., Walsh, J.C. & Sutherland, W.J. (2014) Organising evidence for environmental
 335 management decisions : a '4S' hierarchy. *Trends in Ecology & Evolution*, **29**, 607–613.
- 336 Fancy, S., Gross, J.E. & Carter, S.L. (2009) Monitoring the condition of natural resources in US
 337 national parks. *Environmental Monitoring and Assessment*, **151**, 161–174.
- 338 Fazey, I., Proust, K., Newell, B., Johnson, B. & Fazey, J.A. (2006) Eliciting the Implicit Knowledge
 339 and Perceptions of On-Ground Conservation Managers of the Macquarie Marshes. *Ecology and
 340 Society*, **11**, 25.
- 341 Feld, C.K., Sousa, P., Martins, P., Jose, C.K.F. & Dawson, T.P. (2010) Indicators for biodiversity and
 342 ecosystem services : towards an improved framework for ecosystems assessment. *Biological
 343 Conservation*, 2895–2919.
- 344 Field, S.A., Tyre, A.J., Jonzen, N., Rhodes, J.R. & Possingham, H.P. (2004) Minimizing the cost of
 345 environmental management decisions by optimizing statistical thresholds. *Ecology Letters*, **7**,
 346 669–675.
- 347 Gibbons, P., Briggs, S. V., Ayers, D., Seddon, J., Doyle, S., Cosier, P., McElhinny, C., Pelly, V. &
 348 Roberts, K. (2009) An operational method to assess impacts of land clearing on terrestrial
 349 biodiversity. *Ecological Indicators*, **9**, 26–40.
- 350 Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T. & Ohlson, D. (2012) *Structured
 351 Decision Making: A Practical Guide to Environmental Management Choices*. Wiley-Blackwell,
 352 Oxford.
- 353 Groffman, P., Baron, J., Blett, T., Gold, A., Goodman, I., Gunderson, L., Levinson, B., Palmer, M.,
 354 Paerl, H., Peterson, G., Poff, N., Rejeski, D., Reynolds, J., Turner, M., Weathers, K. & Wiens, J.
 355 (2006) Ecological thresholds: The key to successful environmental management or an important
 356 concept with no practical application? *Ecosystems*, **9**, 1–13.
- 357 Hayes, K., Dambacher, J., Hosack, G., Bax, N., Dunstan, P., Fulton, E., Thompson, P., Hartog, J.,

- Hobday, A. & Bradford, R. (2015) Identifying indicators and essential variables for marine ecosystems. *Ecological Indicators*, **57**, 409–419.
- Hockings, M. (2003) Systems for assessing the effectiveness of management in protected areas. *Bioscience*, **53**, 823–832.
- Landres, P.B., Morgan, P. & Swanson, F.J. (1999) Overview of the Use of Natural Variability Concepts in Managing Ecological Systems. *Ecological Applications*, **9**, 1179–1188.
- Lindenmayer, D.B., Piggott, M.P. & Wintle, B. a. (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.
- Link, J.S. (2005) Translating ecosystem indicators into decision criteria. *ICES Journal of Marine Science*, **62**, 569–576.
- Mace, G.M. & Baillie, J.E.M. (2010) The 2010 Biodiversity Indicators : Challenges for Science and Policy. *Conservation Biology*, **21**, 1406–1413.
- Martin, J., Fackler, P.L., Nichols, J.D., Runge, M.C., Intyre, C.L.M.C., Lubow, B.L., Cluskie, M.C.M.C. & Schmutz, J.A. (2011) An Adaptive-Management Framework for Optimal Control of Hiking Near Golden Eagle Nests in Denali National Park. , 1–8.
- Martin, T.G., Nally, S., Burbidge, A. a., Arnall, S., Garnett, S.T., Hayward, M.W., Lumsden, L.F., Menkhorst, P., McDonald-Madden, E. & Possingham, H.P. (2012) Acting fast helps avoid extinction. *Conservation Letters*, **5**, 274–280.
- Martin, J., Runge, M.C., Nichols, J.D., Lubow, B.C. & Kendall, W.L. (2009) Structured decision making as a conceptual framework to identify thresholds for conservation and management. *Ecological Applications*, **19**, 1079–90.
- Moldan, B., Janoušková, S. & Hák, T. (2012) How to understand and measure environmental sustainability: Indicators and targets. *Ecological Indicators*, **17**, 4–13.
- Morrison, L. (2008) The use of control charts to interpret environmental monitoring data. *Natural Areas Journal*, **28**, 66–73.
- Nie, M. & Schultz, C. (2012) Decision-Making triggers in adaptive management. *Conservation Biology*, **26**, 1137–1144.
- Pazhayamadom, D.G., Kelly, C.J., Rogan, E. & Codling, E. a. (2013) Self-starting CUSUM approach for monitoring data poor fisheries. *Fisheries Research*, **145**, 114–127.
- Pullin, A.S. & Stewart, G.B. (2006) Guidelines for Systematic Review in Conservation and Environmental Management. , **20**, 1647–1656.
- Rumpff, L., Duncan, D.H., Vesk, P.A., Keith, D.A. & Wintle, B.A. (2011) State-and-transition modelling for Adaptive Management of native woodlands. *Biological Conservation*, **144**, 1224–1236.
- Runge, M.C. & Walsh, T. (2014) Identifying Objectives and Alternative Actions to Frame a Decision Problem. *Application of Threshold Concepts in Natural Resource Decision Making* (ed G.R. Guntenspergern), pp. 29–44. Springer, New York.
- Sainsbury, K.J., Punt, A.E. & Smith, A.D.M. (2000) Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science*, **57**, 731–741.
- Scholes, R.J. & Kruger, J.M. (2011) A framework for deriving and triggering thresholds for management intervention in uncertain, varying and time-lagged systems. *Koedoe*, **53**.
- Schwartz, M.W., Cook, C.N., Pressey, R.L., Pullin, A.S., Runge, M.C. & Sutherland, W.J., Williamson, M.. (2017) Decision support frameworks and tools for conservation. *Conservation Letters*.
- Timko, J.A. & Innes, J.L. (2009) Evaluating ecological integrity in national parks: Case studies from Canada and South Africa. *Biological Conservation*, **142**, 676–688.
- Williams, B.K. & Brown, E.D. (2014) Adaptive management: From more talk to real action. *Environmental Management*, **53**, 465–479.
- Woodley, S. (2010) Ecological Integrity and Canada's National Parks. *The George Wright Forum*, **27**, 151–160.
- Worboys, G., Lockwood, M., Kothari, A., Feary, S. & Pulsford, I. (eds). (2015) *Protected Area Governance and Management*. ANU Press, Canberra.

413 **Table 1:** Key steps needed to develop decision triggers and where they align with steps in natural resource management frameworks (using terminology from
414 each framework).

	Decision context	Management Action	Conduct Monitoring	Review and refine
Adaptive Management A decision-making process to develop, trial and select among multiple potentially effective management options (Williams & Brown 2014).	Assess the problem	Design	Implement, Monitor	Evaluate, Adjust
Open Standards Systematic approach to planning, implementing, and monitoring conservation initiatives (Conservation Measures Partnerships 2007).	Conceptualise Plan actions and Monitoring	Plan actions and Monitoring Implement management and Monitoring	Implement management and Monitoring Analyse, Use, Adapt	Analyse, Use, Adapt
Management Strategy Evaluation Modelling based approach to assessing the consequences of a range of different management strategies or options to determine which approach will be the most appropriate to meet the operational objective (Sainsbury, Punt & Smith 2000).	Plan (determine management objectives, define key desired outcomes, identify performance indicators)	Plan (develop management strategies and actions) Do	Do (establish monitoring programs for selected performance indicators) Evaluate and learn (evaluate management effectiveness)	Evaluate and learn (periodically review overall management program) Adjust
Management Effectiveness Evaluation Designed to assist conservation managers to understand, learn from and improve conservation management efforts (Hockings 2003).	Design/Planning (Context and Planning)	Adequacy/Appropriateness (Inputs and Process)	Delivery (Outcomes)	Delivery (Outcomes)

	Decision context	Management Action	Conduct Monitoring	Review and refine
Structured decision-making An approach to identify and evaluate alternatives that focuses on engaging stakeholders, experts (Gregory <i>et al.</i> 2012).	Decision context Define objectives and measures	Develop alternatives Estimate consequences Evaluate trade-offs and select	Implement, monitor and review	Implement, monitor and review
Vital Signs Monitoring Long term resource monitoring of parks (Fancy, Gross & Carter 2009).	Clearly define goals and objectives Compile and summarise existing information Develop conceptual models Prioritise and select indicators	Not applicable	Develop an overall monitoring design Developing monitoring protocols Establish data management, analysis and reporting procedures	Apply monitoring results to natural resource stewardship

416 **Table 2:** Methods available for setting decision triggers

Method	Evidence requirements	Conditions for application	Examples of methods
Computational – Single objective	<p>Scientific evidence (monitoring or research) informing conceptual understanding of how the system works.</p> <p>AND either:</p> <p>Long-term monitoring data to set decision triggers.</p> <p>OR</p> <p>Preliminary monitoring data to set initial decision triggers (using available monitoring data only, bootstrapping techniques, or self-starting control charts) that are updated as new evidence is collected.</p>	<p>Decision triggers represent statistical properties of the baseline data, therefore Type I and II error rates should be explicitly considered.</p> <p>Applicable for the evaluation of single indicators, or multiple indicators that are evaluated independently.</p>	<p>Control charts (Morrison 2008);</p> <p>Statistical thresholds (Field <i>et al.</i> 2004);</p> <p>Thresholds of potential concern (Biggs & Rogers 2003; Scholes & Kruger 2011);</p> <p>Ecosystem based fisheries management decision criteria (Link 2005);</p> <p>Receiver operating characteristic curves (Connors & Cooper 2014).</p> <p>Self-Starting Control Charts (Pazhayamadam <i>et al.</i> 2013).</p>
Computational – Multiple objectives	<p>Scientific evidence (monitoring or research) informing conceptual understanding of how the system works.</p> <p>AND either:</p> <p>Long-term monitoring data to inform model predictions about indicator response to management actions.</p> <p>OR</p> <p>Expert judgment or preliminary monitoring data to inform model predictions about indicator response to management actions.</p>	<p>Useful when decision triggers must be set for an ecological indicator in the face of competing objectives.</p> <p>Expert judgement to set objectives.</p> <p>Optimization models to predict indicator response to alternative management actions.</p> <p>Expert judgement to predict indicator response to alternative management action.</p>	<p>Optimisation modelling (Martin <i>et al.</i> 2009);</p> <p>Multi-objective participatory modelling (Addison, de Bie & Rumpff 2015).</p>

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Method	Evidence requirements	Conditions for application	Examples of methods
<i>Value based</i>	Expert / regulators judgment about minimum acceptable condition of an indicator.	Based on values, where social and political factors play a critical role in systems and override environmental objectives.	Utility thresholds (Martin <i>et al.</i> 2009); Regulatory standards (ANZECC 2000; Moldan, Janoušková & Hák 2012).

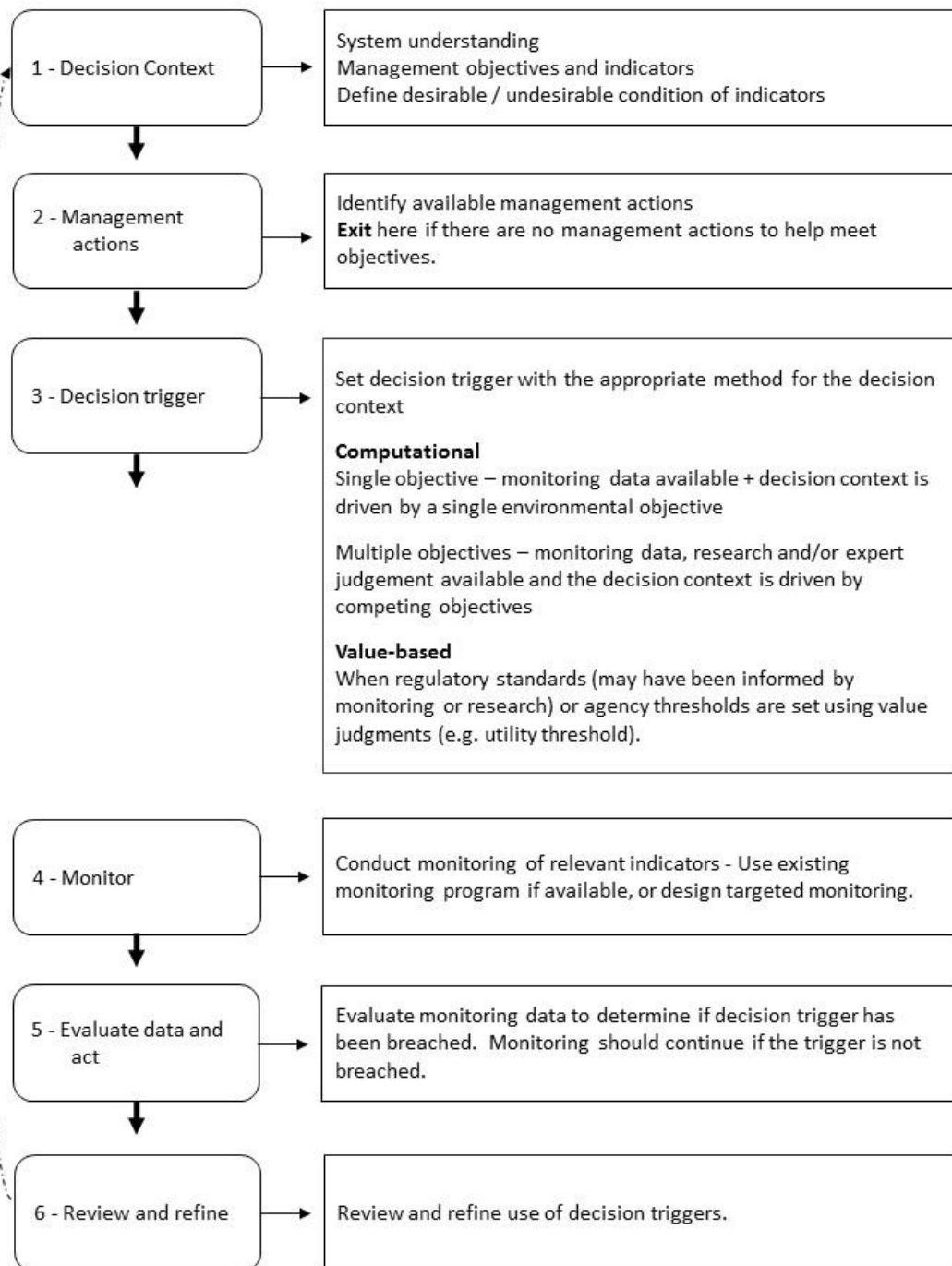
419 **Table 3:** A synopsis of the methods for setting decision triggers

Method	Description	Reference
Control charts	Control charts are widely used in engineering and can be used to assess long term monitoring data and determine whether management intervention is required. A univariate or multivariate sample statistic is plotted through time, with control limits that represent the bounds of variability in the monitored population (e.g., 3 sigma control limits). They can include both warning limits, which indicate small shifts in condition, and action limits which indicate a large shift in condition. Control charts are a suitable approach to apply to both to long term environmental monitoring data sets (e.g., mean control charts, and multivariate control charts), and in situations where limited environmental data is available (e.g., self-starting control charts).	Anderson & Thompson 2004; Morrison 2008; Pazhayamadom <i>et al.</i> 2013
Statistical thresholds	Statistical thresholds represent the value of an indicator need to meet a stated objective about management cost, considering the relative cost of type 1 and type 2 errors. This requires a good understanding of system dynamics (e.g., being able to estimate the probability of change in indicator) and the costs of management actions. This approach has been used to determine management decisions for an economically valuable threatened species.	Field <i>et al.</i> 2004\
Thresholds of potential concern (TPC)	TPC are upper and lower limits of an indicator that define accepted levels of variation in an ecosystem. TPCs are based on natural variation evident from long term monitoring data and a conceptual understanding of system dynamics. They have been applied to protected area management across South Africa, particularly plant and animal dynamics, such as changes in composition and abundance of key species.	Biggs & Rogers 2003; Scholes & Kruger 2011
Ecosystem based fisheries management decision criteria	Multi-indicator triggers, known as warning thresholds and limit reference points, are used in fisheries to support ecosystem level management. Indicators are chosen that represent ecosystem processes and where the impact of fishing on the indicator is understood. Triggers are determined using factors such as maximum and minimum values across a time series or points of inflection in time series trajectories.	Link 2005
Receiver operating characteristic (ROC) curves	ROC curves can be used to develop decision triggers that optimally trade-off type 1 and type 2 errors. The curves are based on observed trends in indicators that reflect status, such as species abundance, distribution and mortality. To develop a ROC curve, the probabilities of true and false positives (correctly/incorrectly classifying a system as a concern), and true and false negatives (correctly/incorrectly classifying a system as not a concern) of an indicator are compared. Decision triggers are identified that optimally trade-off these errors.	Connors & Cooper 2014

Method	Description	Reference
Optimisation modelling	A model of system behaviour that projects the consequences of potential management actions on the system, at a given time. These models can be used to find the optimal management decision (that maximises return) at each time step. For example, using Stochastic Dynamic Programming to identifying the amount of water to be made available for irrigation while maintaining the persistence of wetland species	Martin et al. 2009
Multi-objective participatory modelling	A stakeholder workshop approach using the principles of structured decision making. Designed to be used when management thresholds must be set for environmental indicators in the face of multiple competing objectives, incorporate scientific understanding and value judgments; and when there is limited modelling experience. This approach has been applied to a protected area management issue where the condition of a key ecological feature needed to be balanced with competing social (increasing visitation) and economic (minimizing resources spent on management interventions) objectives.	Addison, de Bie & Rumpff 2015
Utility thresholds	Values of indicators at which small changes result in substantial changes in the value of a management outcome, which is determined by human values. For example, an objective of maintaining a population of a flagship species at a level that will attract visitors to a protected area.	Martin <i>et al.</i> 2009;
Regulatory standards	When the decision trigger is defined according to environmental targets set within regulatory or policy requirements, which may reflect value-based judgements. For example, regulator standards for ecotoxicology levels.	ANZECC 2000; Moldan, Janoušková & Hák 2012

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423 **Fig. 1:** Six steps for developing and implementing decision triggers.