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Selecting indicator species for biodiversity management

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Running heads:

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Selecting indicators for management

Indicator species are frequently used for biodiversity management but whether indicator species selection is explicit about their ability to improve management decisions remains unclear. We reviewed the scientific literature to assess whether existing methods for selecting indicator species account for the following five monitoring and management "decision factors": objectives, constraints, actions, uncertainties, and biodiversity outcomes. Of the selected studies, most focused only on improving monitoring efficiency rather than on management effectiveness, potentially leading to ineffective indicators for decision making; only 21% of the studies explicitly accounted for management objectives and actions. Crucially, 94% of the reviewed studies and one-half of all indicator selection methods overlooked constraints (eg

budgets), as well as uncertainties in indicator responses to management. To improve selection of indicator species, we suggest a systematic approach using key concepts from structured decision making. This approach facilitates explicitly evaluating management outcomes as part of the indicator species selection process and allows for the review of indicator choices over time to improve future monitoring and management decisions.

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In a nutshell:

- Indicator species provide information that can influence decisions for managing specific species, threats, or whole ecosystems
- Current approaches for selecting indicator species generally ignore the management context and do not test the capacity of indicators to improve management decisions
- Ignoring the link between indicator species and management decisions can result in selecting the wrong species, resulting in wasted resources and/or misguided management actions
- Taking lessons from structured decision making, we recommend incorporating management factors into a systematic framework for indicator selection; such an approach will improve monitoring and management decisions over time

Decisions about how to manage biodiversity can be difficult, and the wrong decisions can have unexpected and long-term ramifications for conservation efforts (Lindenmayer *et al.* 2013). Conscious of the risks of making bad decisions, researchers and resource managers often call for detailed monitoring and evaluation to improve their understanding about the state of biodiversity being managed and the processes influencing it. Indicator species (single species and/or groups of species; ie communities, guilds, and taxa) simplify this task by providing proxies for monitoring biodiversity, thereby reducing the scale, intricacy, and expense of monitoring (see Figure 1 for examples; Landres *et al.* 1988; Pereira *et al.* 2013). Hence, the use of indicator species has become a standard monitoring approach in ecological assessment and biodiversity conservation (Caro 2010). However, despite a marked increase in the reliance on indicator species (Siddig *et al.* 2016), it is still unclear how to choose the most appropriate indicator species to inform management decisions (Favreau *et al.* 2006; Rodrigues and Brooks 2007). Moreover, indicator selection is often not straightforward because monitoring different species may lead to different management decisions (Grantham *et al.* 2010). There is therefore a need to develop systematic selection approaches that clearly link monitoring of indicator species to well-defined management decisions (Failing and Gregory 2003). In this review, we outline a framework to improve the consistency and transparency of current approaches used to select indicator species for management, and evaluate the extent to which management decisions are explicitly considered in the selection process.

Existing selection approaches are commonly based on qualitative (Lindenmayer *et al.* 2015) or quantitative (Beliaeff and Pelletier 2011) assessments of indicators against set criteria, such as sensitivity to change, or feasibility of data collection, analysis, and interpretation (Heink and Kowarik 2010; Jones *et al.* 2011). More recent frameworks for indicator selection conceptually link indicators with management actions to inform policy (Nicholson *et al.* 2012) or account for trade-offs between multiple management factors (see Tulloch *et al.* [2011] for an example of balancing the costs of monitoring indicators with the quality of information obtained). However, a general framework for indicator species evaluation and selection – one that systematically incorporates monitoring- and management-related components – is currently lacking.

One approach to guide the selection of effective indicator species is structured decision making (Lyons *et al.* 2008), which embodies a set of tools for systematically analyzing complex problems to support more transparent and robust decisions (Gregory *et al.* 2012). Structured decision making has helped address monitoring questions such as whether and when to monitor (McDonald-Madden *et al.* 2010), how often to monitor (Hauser *et al.* 2006), how to allocate resources for monitoring different species (Wilson *et al.* 2015), and how to target monitoring to resolve key uncertainties (Runge *et al.* 2011). However, it is unclear to what extent such formal approaches are routinely used for the selection and evaluation of indicator species in conservation.

Structured decision making encompasses five basic components (hereafter referred to as “decision factors”; see Table 1): objectives, constraints, actions, uncertainties, and biodiversity outcomes (Gregory *et al.* 2012). Clearly articulating management objectives for indicator selection allows for the evaluation of alternative indicator species by determining whether and to what extent monitoring a species helps to achieve desired management outcomes (Wiens *et al.* 2008; Beliaeff and Pelletier 2011). Considering decision constraints, such as monitoring budgets (Tulloch *et al.* 2013), in addition to whether an indicator species is a good proxy for other species in the community (ie surrogacy; Wiens *et al.* 2008), can help practitioners choose species that are responsive to changes in the system while also being affordable to monitor. Furthermore, uncertainties in the responses of biodiversity to management affect our ability to manage optimally, but can be resolved through monitoring (Regan *et al.* 2002). Biodiversity management can be improved by selecting indicator species that resolve the most uncertainty with respect to the effectiveness of different management actions (Lyons *et al.* 2008).

In this study, we first propose a general framework for the adaptive selection and evaluation of indicator species, following the core tenets of structured decision making, to link indicators to well-defined management decisions. Then, we conduct a systematic review of the scientific literature to assess (1) the extent to which decision factors (ie objectives, constraints, actions, uncertainties, and outcomes) are explicitly considered in the choice of indicator species, and (2) the methods used to select indicator species in these studies. Our primary aim was to identify the successes and gaps in accounting for the management context in indicator species selection and, in doing so, to highlight future opportunities, as well as possible challenges, for improving monitoring and management decisions when indicators are necessary.

Decision framework for indicator selection and evaluation

We first develop a decision framework for indicator selection based on structured decision making to systematically account for key decision factors (Figure 2) via the following steps: (1) define the problem, management objectives, and decision constraints (eg monitoring or management budgets); (2) list alternative management actions (eg threat mitigation or habitat restoration) and identify candidate indicator species; (3) evaluate the expected consequences of alternative management actions and indicator species based on a priori beliefs regarding system dynamics and responses to management, and then select management actions and indicators based on this evaluation; (4) implement selected management and monitoring actions; and (5) evaluate outcomes and update knowledge, management actions, and indicator species through adaptive management. Here, we emphasize the importance of evaluating indicator species to ensure that the selected species help improve management decisions and outcomes over time. Evaluation of indicators and management actions is performed a priori at the start of each loop using analytical tools to estimate the expected management outcomes under different management actions and selected indicator species. Since the ability of different indicators to inform future management may vary with the current choice of management action, in Step 3, management actions are selected first followed by indicator selection. The adaptive design of the framework then allows information obtained from monitoring indicator species in the current time-step to improve management decisions in the next time-step, as facilitated through post-hoc evaluations that compare the expected and observed management outcomes. Using this as a benchmark for our systematic review, we assess which decision factors in our framework are considered by studies that select or evaluate indicator species for management.

Methods

Systematic review methodology

We searched for journal articles published in English between 1 Jan 1990 and 31 Dec 2015, using the keywords (“indicator species” OR “surrogate species”) AND (manage* OR policy OR decision OR action) AND (assess* OR evaluat* OR priorit*) under TOPIC in the ISI Web of Science database. The titles and abstracts of the resulting 519 studies were then examined for inclusion based on whether a study met all three of the following criteria: (1) was about indicator species, (2) aimed to inform the management of biodiversity, and (3) selected or evaluated indicators (see Panel 1 for definitions of search terms). When a study considered multiple types of indicators, we only reviewed article content relating to indicator species (single species and/or groups of species; ie communities, guilds, and taxa). Although studies may use alternate terms such as “ecological indicator” or “bioindicator” (Siddig *et al.* 2016), commonly used terms like “indicator” or “surrogate species” captured a representative subset of studies from the literature (WebTable 1). We excluded studies that focused only on indicators for sustainability, ecosystem services, or social indicators that were not directly related to biodiversity management (see WebFigure 1 for details). The 108 selected studies were then categorized based on whether the decision factors (Table 1) associated with management or monitoring were (1) not considered, (2) discussed only, or (3) explicitly evaluated (categories explained in Figure 3). Unlike other decision factors, uncertainty applies to all steps of the decision-making process (Regan *et al.* 2002; Addison *et al.* 2017). We did not differentiate between different types of uncertainty (eg epistemic and linguistic) nor did we address how uncertainty was dealt with in the studies; however, we did record whether a study considered any kind of uncertainty relating to indicator selection. The method used to select indicator species was also recorded (WebTable 2).

Results

Decision factors considered in indicator selection

In general, studies evaluated indicator species against monitoring objectives (94%; Figure 3) and ignored the management objectives altogether. For example, studies usually focused on establishing indicator species' surrogacy for biodiversity or their sensitivity to anthropogenic pressures (WebFigure 2; eg de la Nuez-Hernandez *et al.* 2014; Brunbjerg *et al.* 2015). Only 21% of studies evaluated indicator species against the stated management objectives and considered alternative management actions. These studies evaluated indicator species for achieving management objectives such as identifying new conservation areas to supplement existing protected area networks (eg Culmsee *et al.* 2014) or reserve selection decisions to minimize species extinctions (eg Nicholson *et al.* 2013). Monitoring actions were always considered and were either implicit (eg alternative indicator species based on data from published studies; Culmsee *et al.* 2014) or explicit (eg surveys to monitor indicator species; Brunbjerg *et al.* 2015). Constraints, such as limited monitoring or management budgets (eg Juutinen and Monkkonen 2004) or limited area available for management (eg Nicholson *et al.* 2013), were rarely considered (Figure 3). Further, only 30% of studies considered monitoring-related uncertainty (eg estimating detection probability of bird species via bird calls; Rempel *et al.* 2016), while management-related uncertainty was generally overlooked (eg parametric or model uncertainty describing indicator response to management actions; but see Tulloch *et al.* [2011]).

Methods used for indicator selection

One-half of the studies used standard statistical methods such as descriptive statistics or correlations for evaluating and selecting indicator species (Figure 4a). For example, de la Nuez-Hernandez *et al.* (2014) compared the mean abundance of a coral species between localities with high and low diving pressure to establish its sensitivity to recreational diving impacts. Multivariate ordination/cluster analysis was the second most common method, of which Indicator Species Analysis (ISA; Dufrene and Legendre 1997) was the most widely used. For instance, ISA was used to differentiate among invertebrate communities in disturbed areas and identify species representative of different types of disturbances (Brunbjerg *et al.* 2015). The most common methods of indicator evaluation (standard statistical methods, ordination/cluster analysis, and regression) were more often used to assess monitoring-related actions, outcomes, and uncertainties than to assess management uncertainties (WebFigure 3). Of the 21 studies that explicitly evaluated indicator species against management objectives, standard statistical methods were again the most common, followed by regression and mathematical optimization methods (Figure 4b). Decision–

analytic methods such as optimization (eg Nicholson *et al.* 2013) and cost–benefit analysis (eg Tulloch *et al.* 2011) were used infrequently, but consistently accounted for both monitoring and management factors (WebFigure 3).

Discussion

When intended to inform management decisions, monitoring is not an end in itself but derives its purpose and value from improvements in decision making (Nichols and Williams 2006). As such, indicator selection needs to move beyond the much-cited discussion on improving measurement accuracy toward a full clarification of the management decision factors that should govern indicator choice (Possingham *et al.* 2012). Despite this need, our review demonstrates that management objectives and actions are rarely considered in indicator species selection (Figure 3). Instead, indicator species were often evaluated only for their monitoring efficiency (eg how well an indicator species represents another species or the ecological community; WebFigure 2). Indicator species chosen this way may lack pragmatic utility in effectively informing decisions to trigger management interventions (Lindenmayer *et al.* 2013). A number of selection methods were able to account for most of the decision factors in the management-related component of the decision (WebFigure 3; see Nicholson *et al.* [2013] for an example that considers all factors except monitoring constraints), but these were rarely applied (Figure 4).

Applying indicator selection as a structured decision-making process

By drawing on the core tenets of structured decision making (Gregory *et al.* 2012), our proposed framework for indicator selection and evaluation (Figure 2) ensures the consideration of factors relating to both monitoring and management decisions. Here, we provide an example illustration of our framework for managing declining small mammals in the Pilbara, Western Australia (Figure 5).

In Step 1, we would describe the problem of small mammal populations declining under the impacts of increasing fire frequency and overgrazing by feral ungulates and domestic herbivores (Panel 2; Carwardine *et al.* 2014). There is uncertainty about which mitigation actions will be most effective in slowing down the population declines, so monitoring is required to better understand the potential responses of mammals to management. The management objective is to minimize the expected number of species in decline, but a monitoring objective could also potentially be specified (eg to minimize uncertainty in the response [population trend] of each species to management). Both management and monitoring are constrained by limited budgets. In Step 2, actions that can be taken to manage fire frequency and to reduce grazing intensity in the Pilbara are identified, as are candidate indicator species that are likely to be indicators of the response of the mammal community to management (Table 2). Possible indicator species include the greater bilby (*Macrotis lagotis*), the northern quoll (*Dasyurus hallucatus*), and the pale field rat (*Rattus tunneyi*) (Figure 6). The set of potential indicator species may be based on expert consultation, empirical data on species occurrence and trends in the region, or available data on species' performances in response to management. In Step 3, management actions (manage fire and/or reduce grazing) are selected to minimize the number of species in decline, given existing information and within budget constraints. For instance, a return-on-investment approach (eg Possingham *et al.* 2012) could identify the most cost effective action(s) achievable within budget constraints. On the basis of the management action chosen, we then select the species to monitor: the one that provides the best information for improving management decisions in the next time-step. For instance, a value of information analysis (an approach to assess the management gains from obtaining new information) could allow us to quantify the value of reducing uncertainty in management outcomes when monitoring the bilby versus the quoll or field rat (Bal *et al.* 2018). In Step 4, the selected threat management actions are implemented and the selected indicator species are monitored. In Step 5, observed responses of the indicator species under the selected management actions are compared to the expectations established in Step 3, and information about the effectiveness of management for each species is updated.

In the first round of application of the framework, several indicator species may need to be monitored in order to identify the species that provide the most improvement in management outcomes across all species considered. Future iterations of this will help narrow down the indicator species that should be monitored, as well as the management actions that most benefit biodiversity. For instance, subsequent evaluation may indicate that *M lagotis* responds to both threats and their management and is therefore a good indicator to inform management actions for all species. Alternately, *M lagotis* may respond only to grazing management, suggesting that either (1) additional species need to be monitored to assess the impacts of fire management for all species or (2) fire management activities have been unsuccessful. The adaptive nature of our framework would enable these uncertainties to be resolved over time. Importantly for indicator species, these evaluations may reveal correlations between responses of multiple species to threats and management, indicating that some species can serve as effective surrogate indicators for achieving management objectives and others less so.

Evaluating management effectiveness of indicators

Commonly favored methods for selecting indicator species, such as regression, correlations, or ordination/cluster analysis (Figure 4), do not aid in the integration of the multiple decision factors inherent in most selection-oriented problems (WebFigure 3), and therefore do not constitute a decision-making framework (Gregory *et al.* 2012). Selecting indicators that are relevant to the decision context requires evaluating their management effectiveness before implementing management actions. This involves using methods or models to estimate the expected improvement in management outcomes as a result of monitoring alternative indicators (Step 3) while at the same time accounting for uncertainty in management effectiveness. These models need not always be quantitative (eg Tulloch *et al.* 2011), as even simple conceptual (eg Nicholson *et al.* 2012) and qualitative (eg Hayes *et al.* 2015) models can provide a good foundational understanding of cause–effect relationships in ecological systems and a means to explore the uncertainty in the decision-making process (Addison *et al.* 2013). In some cases, formal decision–analytic tools offer an objective approach to identify indicators and management actions that can enhance management outcomes, yet these methods have seen little uptake in indicator species selection (Figure 4; eg economic decision frameworks such as cost–benefit analysis and mathematical optimization; see Maron *et al.* 2013; Field *et al.* 2004). The valuation of indicators using value of information analysis (eg Maxwell *et al.* 2015; Bal *et al.* 2018) also provides a formal way to quantify the management benefits of monitoring alternative indicator species.

Importantly, indicators evaluated against management thresholds (ie a level of change in the environment or biodiversity metric that triggers conservation action) can assist managers in making difficult decisions about when to intervene in ecosystems to address undesirable changes (Lindenmayer *et al.* 2013). Models used to set decision triggers, evaluate indicators, and inform management can be statistical or decision–analytic in nature (de Bie *et al*. 2018), and these should be embedded in an overarching process for indicator selection and evaluation (Figure 2).

Iterative learning and selection of indicators

Adaptive management and iterative monitoring frameworks facilitate learning-based decision making such that subsequent actions can be adjusted based on what has been previously learned (Lyons *et al.* 2008; Williams 2011). For example, Hauser *et al.* (2006) demonstrated how monitoring effort to inform the management of red kangaroos (*Macropus rufus*) in South Australia changed according to prior knowledge of the population density of kangaroos in the previous year, and also according to the number of years between successive surveys. Similarly, indicator species need to be reviewed and updated to respond to the dynamic nature of ecological systems and decision processes (Williams 2011). However, our review found no examples of adaptive selection of indicator species over time.

In contrast to a more surveillance-type approach that monitors the state of biodiversity at a specific point in time, our proposed approach is an adaptive framework, in which the process of framing the objectives and the monitoring design, as well as interpreting new information, are iterative (see the "Learn and Review" loop in Figure 2; Ringold *et al.* 1996). This is because the data needed to inform selection or updating of indicators and management actions will often (but not always) come from the monitoring of the indicator species themselves. The adaptive component of our framework comes into play if decisions are recurrent and the structured decision process identifies critical uncertainties that, if resolved, have the potential to improve subsequent indicator choices (Step 5). This can be facilitated through feedback loops to (1) clarify and learn about uncertainty associated with model parameters, and evaluate the true effectiveness of indicator species and management actions; and (2) review the decision context where necessary (de Bie *et al*. 2018).

Barriers and opportunities

Applying structured decision making to monitoring decisions is a relatively new approach in conservation as compared with its application in other disciplines, such as medicine or economics. This may explain why methods such as cost-effectiveness analysis are rarely used to compare different indicator choices (Figure 4), despite being well documented (Edwards *et al.* 2007). To facilitate the adoption of structured decision making for indicator species selection, scientists need to play a bigger role in communicating both the benefit of using the appropriate tools (Addison *et al.* 2013) as well as the risks of failing to link indicators to management questions (Lindenmayer *et al.* 2013). In addition, building partnerships between scientists, statisticians, policy makers, and resource managers can help to identify policy- and management-relevant reasons for monitoring, as well as to develop scientifically robust approaches for the selection of cost-effective indicators (Lindenmayer and Likens 2010; Addison *et al*. 2017). In the context of structured decision making, however, adequate funding is required to maintain long-term monitoring programs, which poses a major challenge for practitioners of biodiversity conservation (Lindenmayer and Likens 2010).

Most decision–analytic methods rely heavily on the use of mathematical models that require a substantial degree of technical expertise (Addison *et al*. 2013). In response, scientists have begun to develop user-friendly tools and software to make modeling-intensive methods more accessible to non-specialist users (Canessa *et al*. 2015; Di Fonzo *et al*. 2017). Alternatively, a collaborative approach between scientists and conservation practitioners to carry out the modeling and monitoring components of the work (Runge *et al*. 2011) can also enable the use of the most up-to-date decision–theoretic methods for indicator selection.

Finally, choices are often made based on decision makers' beliefs and values, habits, or preferences rather than solely in accordance with scientific methods (Failing and Gregory 2003; Gregory *et al.* 2012). Although we identified recent research advances for developing robust indicator selection approaches, reviewing management plans and/or interviewing decision makers could provide valuable insights into opportunities to integrate decision factors more formally into indicator selection in real-world monitoring and management decisions.

Conclusion

With increasing pressure on practitioners to take timely conservation actions, the need for systematic approaches to select indicator species that can best inform biodiversity management is paramount. Our study proposes a decision framework for indicator selection and evaluation that draws on the core tenets of structured decision making to ensure that selected indicator species are relevant to the decision process. Ultimately this will lead to improvements in management and monitoring decisions over time, and justify cost-effective spending of scarce resources.

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References

Addison PFE, Rumpff L, Bau SS, *et al*. 2013. Practical solutions for making models indispensable in conservation decision-making. *Divers Distrib* **19**: 490–502.

Addison PFE, Collins DJ, Trebilco R, *et al*. 2017. A new wave of marine evidence-based management: emerging challenges and solutions to transform monitoring, evaluating, and reporting. *ICES J Mar Sci* **75**: 941–52.

Bal P, Tulloch AIT, Chadès I, *et al*. 2018. Quantifying the value of monitoring species in multi-species, multi-threat systems. *Methods Ecol Evol* **9**: 1706–17.

Beliaeff B and Pelletier D. 2011. A general framework for indicator design and use with application to the assessment of coastal water quality and marine protected area management. *Ocean Coast Manage* **54**: 84–92.

Brunbjerg AK, Jorgensen GP, Nielsen KM, *et al*. 2015. Disturbance in dry coastal dunes in Denmark promotes diversity of plants and arthropods. *Biol Conserv* **182**: 243–53.

Burgass MJ, Halpern BS, Nicholson E, and Milner-Gulland EJ. 2017. Navigating uncertainty in environmental composite indicators. *Ecol Indic* **75**: 268–78.

Canessa S, Guillera-Arroita G, Lahoz-Monfort JJ, *et al*. 2015. When do we need more data? A primer on calculating the value of information for applied ecologists. *Methods Ecol Evol* **6**: 1219–28.

Caro T. 2010. Conservation by proxy: indicator, umbrella, keystone, flagship, and other surrogate species. Washington, DC: Island Press.

Carwardine J, Nicol S, Van Leeuwen S, *et al.* 2014. Priority threat management for Pilbara species of conservation significance. Brisbane, Australia: CSIRO.

Culmsee H, Schmidt M, Schmiedel I, *et al*. 2014. Predicting the distribution of forest habitat types using indicator species to facilitate systematic conservation planning. *Ecol Indic* **37**: 131–44.

de Bie K, Addison PFE, and Cook CN. 2018. Integrating decision triggers into conservation management practice. *J Appl Ecol* **55**: 494–502.

de la Nuez-Hernandez D, Valle C, Forcada A, *et al*. 2014. Assessing the erect bryozoan *Myriapora truncata* (Pallas, 1766) as indicator of recreational diving impact on coralligenous reef communities. *Ecol Indic* **46**: 193–200.

Di Fonzo MMI, Nicol S, Possingham HP, *et al*. 2017. Cost-effective resource allocator: a decision support tool for threatened species management. *Parks* **23**: 101–13.

Dufrene M and Legendre P. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecol Monogr* **67**: 345–66.

Edwards W, Miles RF, and Von Winterfeldt D. 2007. Advances in decision analysis: from foundations to applications. Cambridge, UK: Cambridge University Press.

Failing L and Gregory R. 2003. Ten common mistakes in designing biodiversity indicators for forest policy. *J Environ Manage* **68**: 121–32.

Favreau J, Drew CA, Hess G, *et al*. 2006. Recommendations for assessing the effectiveness of surrogate species approaches. *Biodivers Conserv* **15**: 3949–69.

Field SA, Tyre AJ, Jonzen N, *et al*. 2004. Minimizing the cost of environmental management decisions by optimizing statistical thresholds. *Ecol Lett* **7**: 669–75.

Grantham HS, Pressey RL, Wells JA, and Beattie AJ. 2010. Effectiveness of biodiversity surrogates for conservation planning: different measures of effectiveness generate a kaleidoscope of variation. *PLoS ONE* **5**: e11430.

Gregory R, Failing L, Harstone M, *et al*. 2012. Structured decision making: a practical guide to environmental management choices. Chichester, UK: Wiley-Blackwell.

Hauser CE, Pople AR, and Possingham HP. 2006. Should managed populations be monitored every year? *Ecol Appl* **16**: 807–19.

Hayes KR, Dambacher JM, Hosack GR, *et al*. 2015. Identifying indicators and essential variables for marine ecosystems. *Ecol Indic* **57**: 409–19.

Heink U and Kowarik I. 2010. What criteria should be used to select biodiversity indicators? *Biodivers Conserv* **19**: 3769–97.

Jones JPG, Collen BEN, Atkinson G, *et al*. 2011. The why, what, and how of global biodiversity indicators beyond the 2010 target. *Conserv Biol* **25**: 450–57.

Juutinen A and Monkkonen M. 2004. Testing alternative indicators for biodiversity conservation in old-growth boreal forests: ecology and economics. *Ecol Econ* **50**: 35–48.

Landres PB, Verner J, and Thomas JW. 1988. Ecological uses of vertebrate indicator species: a critique. *Conserv Biol* **2**: 316–28.

Lindenmayer D, Pierson J, Barton P, *et al*. 2015. A new framework for selecting environmental surrogates. *Sci Total Environ* **538**: 1029–38.

Lindenmayer DB and Likens GE. 2010. The science and application of ecological monitoring. *Biol Conserv* **143**: 1317–28.

Lindenmayer DB, Piggott MP, and Wintle BA. 2013. Counting the books while the library burns: why conservation monitoring programs need a plan for action. *Front Ecol Environ* **11**: 549–55.

Lyons JE, Runge MC, Laskowski HP, and Kendall WL. 2008. Monitoring in the context of structured decision-making and adaptive management. *J Wildlife Manage* **72**: 1683–92.

Maron M, Rhodes JR, and Gibbons P. 2013. Calculating the benefit of conservation actions. *Conserv Lett* **6**: 359–67.

Maxwell SL, Rhodes JR, Runge MC, *et al*. 2015. How much is new information worth? Evaluating the financial benefit of resolving management uncertainty. *J Appl Ecol* **52**: 12–20.

McDonald-Madden E, Baxter PWJ, Fuller RA, *et al*. 2010. Monitoring does not always count. *Trends Ecol Evol* **25**: 547–50.

Nichols JD and Williams BK. 2006. Monitoring for conservation. *Trends Ecol Evol* **21**: 668–73.

Nicholson E, Collen B, Barausse A, *et al*. 2012. Making robust policy decisions using global biodiversity indicators. *PLoS ONE* **7**: e41128.

Nicholson E, Lindenmayer DB, Frank K, and Possingham HP. 2013. Testing the focal species approach to making conservation decisions for species persistence. *Divers Distrib* **19**: 530–40.

Pereira HM, Ferrier S, Walters M, *et al*. 2013. Essential biodiversity variables. *Science* **339**: 277–78.

Possingham HP, Wintle BA, Fuller RA, and Joseph LN. 2012. The conservation return on investment from ecological monitoring. In: Lindenmayer D and Gibbons P (Eds). Biodiversity monitoring in Australia. Melbourne, Australia: CSIRO.

Regan HM, Colyvan M, and Burgman MA. 2002. A taxonomy and treatment of uncertainty for ecology and conservation biology. *Ecol Appl* **12**: 618–28.

Rempel RS, Naylor BJ, Elkie PC, *et al*. 2016. An indicator system to assess ecological integrity of managed forests. *Ecol Indic* **60**: 860–69.

Ringold PL, Alegria J, Czaplewski RL, *et al*. 1996. Adaptive monitoring design for ecosystem management. *Ecol Appl* **6**: 745–47.

Rodrigues ASL and Brooks TM. 2007. Shortcuts for biodiversity conservation planning: the effectiveness of surrogates. *Annu Rev Ecol Evol S* **38**: 713–37.

Runge MC, Converse SJ, and Lyons JE. 2011. Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. *Biol Conserv* **144**: 1214–23.

Siddig AAH, Ellison AM, Ochs A, *et al*. 2016. How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in ecological indicators. *Ecol Indic* **60**: 223–30.

Tulloch A, Possingham HP, and Wilson K. 2011. Wise selection of an indicator for monitoring the success of management actions. *Biol Conserv* **144**: 141–54.

Tulloch AIT, Chadès I, and Possingham HP. 2013. Accounting for complementarity to maximize monitoring power for species management. *Conserv Biol* **27**: 988–99.

Wiens JA, Hayward GD, Holthausen RS, and Wisdom MJ. 2008. Using surrogate species and groups for conservation planning and management. *BioScience* **58**: 241–52.

Williams BK. 2011. Passive and active adaptive management: approaches and an example. *J Environ Manage* **92**: 1371–78.

Wilson HB, Rhodes JR, and Possingham HP. 2015. Two additional principles for determining which species to monitor. *Ecology* **96**: 3016–22.

Supporting Information

Additional, web-only material may be found in the online version of this article at

[Note to SPS: please embed Figure 1 within Panel 1]

Figure 1. (a) Bengal tiger (*Panthera tigris tigris*); (b) dark blue tiger butterfly (*Tirumala septentrionis*); (c) controlled burning as part of the Yawuru Indigenous Protected Area (IPA) program effort to reduce the incidence of damaging wildfires.

Photo credits:

(a) © M Gala

(b) © T Varghese

(c) © Yawuru Land and Sea staff

Figure 2. Decision framework for indicator selection and evaluation based on the structured decision-making approach (Gregory *et al*. 2012). Decision factors are highlighted in red (see Table 1 for definitions). The dagger (†) denotes steps where indicators are selected (Step 3), whereas the asterisk (*) denotes where indicators are used to evaluate management outcomes (Steps 3 and 5). See WebFigure 4 for more details.

Figure 3. Percentage of studies considering the (a) monitoring-related and (b) management-related decision factors for indicator selection (see Table 1 for definitions of decision factors). “Not considered” indicates that the decision factor was not mentioned in the study; “discussed only” indicates that the factor was mentioned or discussed qualitatively but not included quantitatively in indicator evaluation and subsequent selection; and “explicitly

evaluated" indicates that the factor was quantitatively included in indicator evaluation and subsequent selection. When monitoring or management objectives were explicitly evaluated, the corresponding outcomes were estimated (categorized as "explicitly evaluated"), and if objectives were discussed or not considered, the outcomes were not estimated (categorized as "not considered").

Figure 4. Frequency of use of indicator selection methods in (a) all studies considered in the review and (b) studies evaluating the indicator against management outcomes. Categories used for methods are not mutually exclusive (see WebTable 2 for definitions).

[Note to SPS: please embed Figure 5 within Panel 2]
Figure 5. Examples of the diversity of the Pilbara landscape. (a) Gorge country; (b) Red Hill station.

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(a) © S Murphy
(b) © L Corker

[Note to SPS: please embed Figure 6 within Panel 2]
Figure 6. Candidate indicator species in the Pilbara, including (a) the greater bilby (*Macrotis lagotis*), (b) the northern quoll (*Dasyurus hallucatus*), and (c) the pale field rat (*Rattus tunneyi*).

Photo credits:
(a) © Save the Bilby Fund
(b) © J Lochman
(c) © S Murphy

Table 1. Decision factors considered in indicator selection based on structured decision making (Gregory *et al.* 2012)

Decision factor	*Definition*	*Monitoring-related example*	*Management-related example*
Objectives	Intentions, aims, or goals for biodiversity conservation	Estimate the number of species present in a given area	Minimize the number of species declining in a given area
Constraints	Factors that limit conservation objectives and actions (eg policy, financial, logistical, or ethical)	Limited resources, including budget, personnel, or time	Limited resources, limited area available for management intervention, time limit within which objective needs to be achieved
Actions	Alternative actions to choose from in order to achieve the objectives	Indicator species use or monitoring, remote sensing	Manage threats causing species declines (eg fire control or invasive weed removal)
Uncertainties	Ambiguity in observability and knowledge of the system	Observation or detection error, noise in the system (stochasticity), poor information on how the system might evolve over time	Poorly known efficiency of management actions (feasibility), poor information on how the system will respond to actions (effectiveness)
Outcomes	Consequences of decisions or actions	Assessment of species abundance within a given area	Reduced species declines within an area

Table 2. Threats, management actions, and indicator species in the Pilbara

Threats	*Management actions*[*]	*Indicator species*[*]
Increased fire frequency	Control burning	*Macrotis lagotis*
Overgrazing	Feral ungulate management	*Dasyurus hallucatus*, *Rattus tunneyi*

Notes: [*]Management actions and indicator species listed are for illustrative purposes only.

Panel 1. Operational definitions of search terms adopted for the systematic review

Indicator species are single species or groups of species used to represent other species or aspects of the environment that are too difficult, inconvenient, or expensive to monitor directly (Landres *et al*. 1988). Species- or environment-related characteristics represented may include qualitative or quantitative variables that provide simple and reliable means to express the attainment of a conservation objective or the results stemming from a specific change (Caro 2010). Metrics may be used to record a directly observable characteristic of species or communities, such as abundance or diversity (Pereira *et al*. 2013), or they may be combined within a formula to provide a composite indicator (Burgass *et al*. 2017). Common examples of indicator species include charismatic species such as the tiger (Figure 1a) and taxonomic groups like butterflies (Figure 1b). We use the term surrogate species synonymously for the purpose of this review.

Management implies policies, decisions, or actions to prevent or reduce biodiversity loss. This includes conservation management actions (eg establishing protected areas, controlling invasive species, controlled burning; Figure 1c) and resource management actions aimed at conserving biodiversity (eg fisheries management).

Evaluation implies a qualitative or quantitative assessment or prioritization of indicators with respect to their specified role (eg surrogacy for other species, ability to detect change, ability to track response to management intervention), which might also include comparing indicators against each other.

Panel 2. Threat management and monitoring in the Pilbara region of Western Australia

Problem context

Populations of critical weight-range species are declining in the Pilbara, Western Australia (Figure 5), due to increasing fire frequency and overgrazing by feral ungulates and domestic herbivores (Carwardine *et al*. 2014). However, there is uncertainty about which threat mitigation actions are most effective in reducing the population declines of these species. Monitoring is required to better understand how the species respond to these actions. The management objective is to minimize the number of species in decline. A monitoring objective may also be specified (eg minimize uncertainty in the response [population trend] of each species to actions). Both management and monitoring are constrained by limited budgets.

Alternatives

Actions to mitigate the threats in the Pilbara are identified, such as controlled burning and feral ungulate management. Candidate indicator species (Figure 6) are also identified from among the species that have known distributions within the study region and are listed as vulnerable by the Australian Environment Protection and Biodiversity Conservation Act to the two threats.

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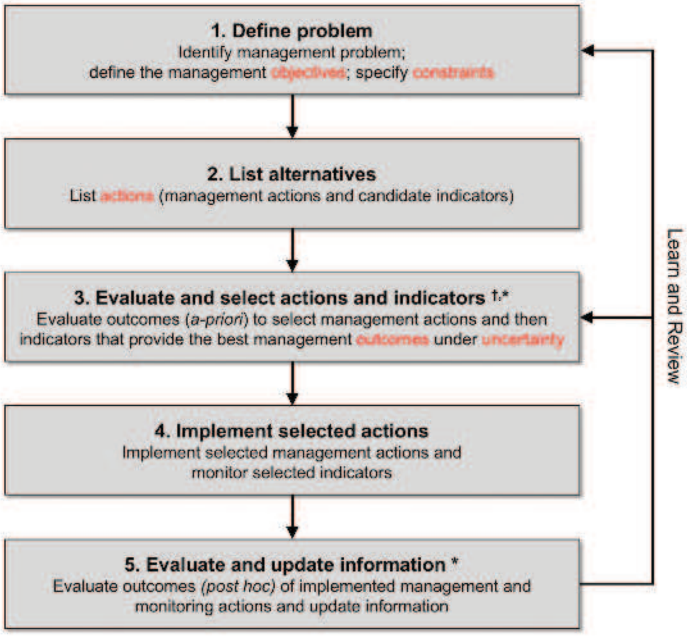

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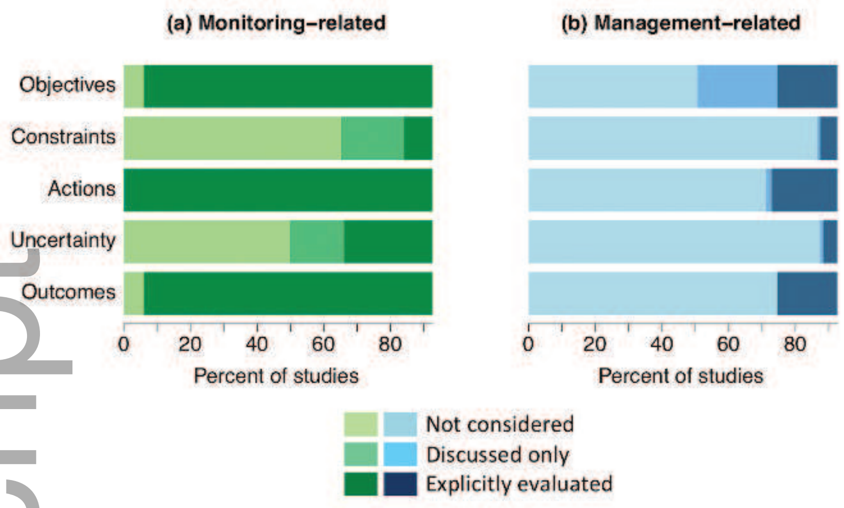

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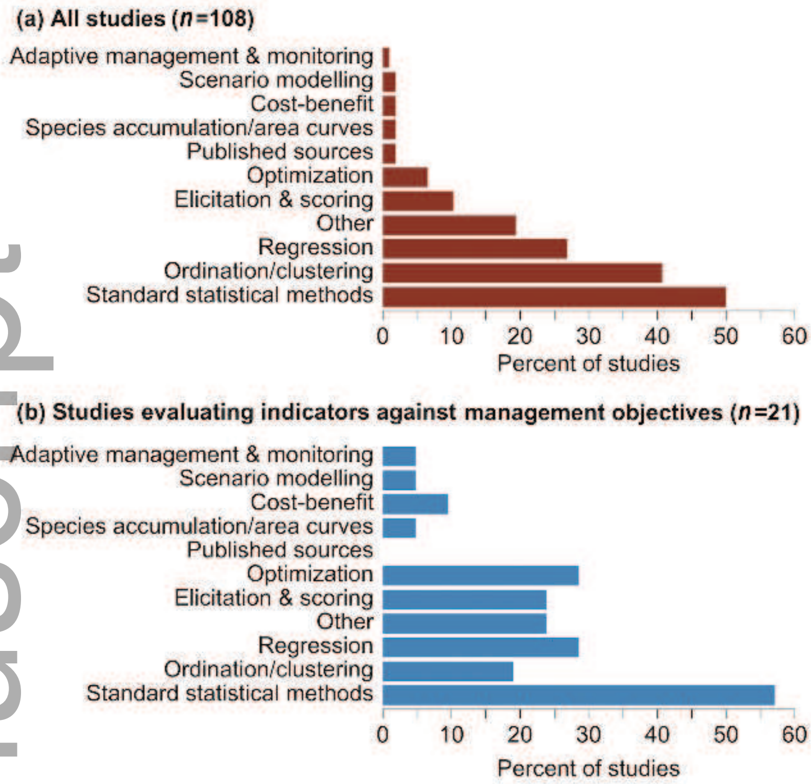

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