The effects of judgment and choices during decision-making for nature conservation

Submitted in total fulfillment of the requirements of the degree of Doctor of Philosophy

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November 2024

There is nothing either good or bad – but thinking makes it so

- Hamlet

~ * ~

To my dad, whose love for nature lives on in me

~ * ~

Declaration

This is to certify that this thesis contains my original work that I conducted towards the degree of Doctor of Philosophy, unless stated explicitly otherwise.

Due acknowledgement has been made in the text to all other materials and references used.

I confirm that this thesis consists of less than 100.000 words in length, exclusive of tables, maps, captions, bibliography and appendices.

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Abstract

Despite increasing efforts in research, implementation, and investment into conservation, many ecosystems and species continue to show a worsening trend. At the same time, a reproducibility crisis has been detected in many scientific disciplines, including ecology and conservation, highlighting difficulties in reproducing the same results when studies or experiments are repeated. Most conservation problems are rooted in complex interactions of socio-ecological systems, for which many cause-and-effect relationships are not fully understood. The uncertainties in available models and data, as well as often competing multiple objectives, introduce human values and judgments into the planning process. Most ecologists and conservation scientists or practitioners are not trained in psychology or decision-making and might not be aware of the impacts that cognitive biases and unstructured thinking can have on decision-making when left unmitigated.

Together, these realizations raise the question of how robust processes are that identify solutions to conservation problems. This thesis explores different ways in which judgment-based choices can influence decision-making for nature conservation. Each of the four chapters investigates a different type of implication that choices within different decision-making steps can have on the final decision made and what possibilities exist to identify and understand these implications and include them in a transparent way in the decision process.

This thesis examines four different aspects:

- The choice of context included in the analysis of data and the impact on identified patterns,
- The choice of decision-making framework and the impact on the frequency with which decision-theoretic criteria get documented in publications,

- The impact of personal judgment during the interpretation of text on collated qualitative data produced typically for systematic literature reviews and assessment of reliability, and
- The possible improvements that a robust decision-making framework application can have for the more recent conservation problem of marine debris, for which many applications lack nuanced and meaningful objectives.

The chapters provide input to an urgently needed recalibration of the ongoing discussion on the most beneficial current and future conservation efforts and how decision-making processes can be improved. Critical reflection of current conservation practice and improvement of decision-making processes might give decision-makers better chances to find the best way forward to bend the curve from the ongoing loss of biodiversity towards a regenerative path.

Acknowledgements & Thanks:

Supervision and advice

Brendan Wintle & Eric Treml: for helping me grow as a scientist, finding access to my own ideas, and developing trust in my abilities to ride without training wheels (well almost).

Fiona Fidler, Steve Kambouris, Bonnie Wintle, Libby Rumpff, Vic Hemming: for their incredibly valuable help with sussing out the details.

Mick Keough for his calm expertise on all admin matters and during my panel meetings.

Labs

Qaeco: for being such an open, friendly, supportive, incredibly smart and fun environment.

Mseac: for the marine angle, and many chats about PhD life.

Individuals

Hugh Possingham: for always finding the time to listen to my ideas and providing feedback.

Paul Slovic: amazing experience to be allowed to talk face to face for over an hour.

Mark Burgman: thank you for taking the time to chat with me about my ideas and challenge me ruthlessly in such a friendly way.

The Nature Conservancy: despite not going ahead, I am thankful for the time and openness I could discuss my initial ideas, which helped me immensely in finding out what I am passionate about.

The Melbourne Statistical Consulting Platform: for being available for initial discussions about study design.

The Benioff Ocean Initiative (Molly Morse, Win Cougar, Erika): for being available to discuss my ideas and signaling interest in using results from my case study on marine debris.

Yoshihisa Kashima: for discussing my early ideas with me and adding the views of a social scientist and psychologist.

David Squire: for investigating the labyrinth of market basket analysis with me.

My parents: For raising me with a curious mind and encouraging me to walk the world on my own path. For always being there for me.

Darren C. Fisher: for the chapter illustrations, and for all the color in my life.

Funding and awards

My PhD candidature was funded by the *Research Training Program Scholarship*, which enabled me to work on my PhD for 4 years, for which I am very thankful. I am also incredibly thankful for the generous extension of my scholarship to account for the impact of the pandemic and other challenges that I encountered during the course of my PhD. Chapter 2 was only made possible by the generous funding of the *John Hodgsons Scholarship*, which enabled me to re-remunerate 4 students with a fair salary for their contribution to the inter-rater reliability study.

I am also grateful for having received a travel grant to attend an international conference (worldbiodiversityforum in Switzerland), the *Stuart White Scholarship*, and the *McBain Award*.

I won the prize for best student talk and best research impact at the 2021 virtual BioSciences PostGrad Symposium for my talk on marine debris (chapter 4), and the second prize in a student art competition with a painting on mental health (2019).

Conferences and presentations

Deliberation, Belief Aggregation, and Epistemic Democracy (DBAED II), Tuesday, 11 June to Thursday, 13 June 2019 at the Maison Internationale de la Recherche of the Université de Cergy-Pontoise (participating only)

University of Melbourne Student Conference 2019 (presenting & organizing committee, presenting chapter 2)

Worldbiodiversityforum, February 2020. Presenting and session organizer, presenting chapter 2.

University of Melbourne Domain Meeting, December 2020, 10 min talk presenting chapter 3.

University of Melbourne Student Conference, September 2021. Speed talk presenting chapter 4.

University of Melbourne 3 Minute Thesis Competition, May 2021. Video presenting chapter 4.

Publications

Beher, Treml, Wintle (2025) Decision-science navigates trade-offs between environmental and socio-economic objectives for marine debris mitigation, Pacific Conservation Biology 31 (1), https://doi.org/10.1071/PC24057

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Article in the online science magazine "The Conversation" (2019) *How to have better arguments about the environment or anything else* https://theconversation.com/ comic-how-to-have-better-arguments-about-the-environment-or-anything-else-98554

Preface

This thesis contains six chapters, a general discussion, four research chapters, and a general conclusion section. In most parts I use the collective pronoun "we" to acknowledge the contributions of my supervisors.

Published chapters

Research chapter three has been published in the journal Conservation Science and Practice. The paper is available as open access publication via the journal's website (https://doi.org/10.1111/csp2.13170). It had been previously submitted to Conservation Letters and Conservation Biology, where it was sent out to peer review, and I received helpful comments from several anonymous reviewers that helped to improve the framing of the paper. The text in this document is the same as in the published paper. As the primary author, I developed the coding scheme, database and code for all figures and tables, as well as the outline of the initial manuscript (total contribution: 90%). The manuscript was further edited and developed with the help of Professor Brendan Wintle and Dr. Eric Treml. Early results were presented in 2020 at the Worldbiodiversityforum in Davos, Switzerland, where I organised and chaired a session on decision-making for conservation actions. As for chapter two and three, the initial overall work on the systematic review, including design of clear variable and categories, benefited from discussions with Professor Mark Burgman, Dr. Bonnie Wintle and Professor Fiona Fidler. All reviewers' comments and responses are made available in Appendix V.

Research chapter four has been published in the journal PlosOne. The idea for the chapter came from discussions with Bonnie Wintle and Fiona Fidler on the coding scheme, and good process for conducting a structured review. I was able to secure funding through the *John Hodgsons Scholarship* to conduct the described experiment. Early results were presented during a School of Bioscience meeting where it was met with great interest for its implications for learning and teaching students. As the main author, I developed the experimental set up, hired students, conducted the experiments, developed all code to produce figures and tables and wrote the outline of the manuscript (total contribution: 85%). I benefited greatly from discussions with fellow PhD candidate Steven Kambouris who helped me to navigate the mathematical nuances of interrater-reliability metrics. Fiona Fidler and Brendan Wintle helped to shape the manuscript. I also thank the four raters Jessica Keem, Erin Bernadette Thomas, Diego Brizuela Torres and Matthew Paul Whitney for participation. Thanks to Dr. Bonnie Wintle for her help in revising the coding scheme. Data and code are publicly available on figshare [https://doi.org/10.6084/m9.figshare.26889553.v1].

Research chapter five has been published in the journal Pacific Conservation Biology. A brief article summarising the study to a general audience has been published via the globalwaterforum (https://www.globalwaterforum.org/2025/02/27/picking-up-plastic-decision-science-navigates-the-trade-offs/). As the primary author, I prepared all code for any figures and tables. The modelling of ocean currents drew on Dr. Eric Treml's body of work. I also outlined the manuscript and supplementary material (Total contribution: 90%). Repeated rounds of review with the help of Dr. Eric Treml, Professor Brendan Wintle, and Dr. Kay Critchell helped to shape up the manuscript. I also thank Maria Beger and Iliana Colette for valuable feedback on the manuscript. Many thanks to Win Cowgar from the University of California, Molly Morse from the Benioff Ocean Initiative, and Erika Scelfo from TerraCycle for the helpful engagement in the early stages of our study. Early results were presented at the Student Conference of the School of Biosciences in 2021, where I won the prize for the best talk. Data and code used to produce results are available on figshare (https://doi.org/10.6084/m9.figshare.26491714.v1). All reviewers' comments and responses are made available in Appendix VI.

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Chapter 1

General introduction

The implications of choices made in decision-making processes for nature conservation.

Urgent decisions on wicked problems

"Wicked" problems are characterized by having no clear solutions, being linked to many other problems, including numerous interacting elements, and being embedded in socio-ecological systems with no clear boundaries (Game et al. 2014; Rittel and Webber 1973). Scientists from varied disciplines including psychology, economy, mathematics, medicine, and ecology have worked for decades on the subject of making good decisions under uncertainty (Arvai et al. 2001; Bekker et al. 2003; Herek et al. 1987; Lipshitz and Strauss 1997; Regan et al. 2005; Schafer and Crichlow 2002; Tversky and Kahneman 1974; 1992; Volz and Gigerenzer 2012; Árvai et al. 2024; Luan et al. 2019; Gigerenzer 2025a). Despite these interdisciplinary efforts and the advances in technology and software, adequately addressing of real-world complexity in decision problems remains a challenge in all sectors (Keefer et al. 2004; Corner and Kirkwood 1991). It is no surprise that many of the environmental problems of today fall under the category of "wicked" problems, and the complexity of problem contexts is still considered one of the top ten barriers for science to inform conservation policy (Rose et al. 2018). While some conservation management plans lead to the intended outcomes, others end in failure (Catalano et al. 2019; Langhammer et al. 2024; Knight et al. 2008; Sutherland et al. 2020). Current efforts in implementing conservation actions to curb the decline in many species and ecosystems around the world have not been able to halt and reverse the negative trends. Measuring effectiveness is often not attempted when conservation actions are implemented, and even when it is, insights can be inconclusive (Karlsdóttir et al. 2021; Catalano et al. 2019; Knight et al. 2008). Therefore, apart from individual case studies that can explain success or failure, the specific reasons for the lack of success of implemented conservation actions at a large scale are not known.

Regardless of these challenges, conservation management decisions must be made to halt and reverse the accelerating biodiversity crisis through effective management actions across the world (UN Environment 2019; Leclère et al. 2020; WWF 2020). Decisions on which conservation actions should be taken, at what time, and at which location are made under severe constraints of time and budgets, and facing uncertainty around many aspects of problem context (Ferraro and Pattanayak 2006; Waldron et al. 2013; Carwardine et al. 2008; Hemming et al. 2022; Ben-Haim 2023; Margules and Usher 1981; Buckley and Forbes 1979). Unfortunately, it is not always clear which actions are most likely to stop or mitigate drivers of biodiversity loss, such as deforestation, pollution or overexploitation in different locations around the world (Maxwell et al. 2016). The reason for that is that the underlying drivers in human societies, as well as the responses of the ecosystems, tend to be context-dependent, which makes the prediction of general outcomes difficult. Consequently, management strategies need to be matched to the individual local problem contexts. Uncertainties in the problem context of most environmental problems are not only rooted in the complexity of the natural world and the scientific mechanistic understanding of social-ecological systems, but are also linked to complexities within the decision process itself, including different management options, competing values of stakeholders, and different analysis methods that can produce a range of possible alternative scenarios for the future (Conroy et al. 2008). However, neither the urgency of the situation nor the complexity of the task should be taken as an excuse for hasty decisions without rigorous planning and identification of those management alternatives that promise feasible positive outcomes for biodiversity by halting or reversing ongoing declines. On the contrary, because the planning process can already plan and mitigate many risks when rigorous processes are applied, it seems like a timely endeavor to assess how details in common decision processes are described, and which impact different aspects of judgments and values can have on planning and prioritization of actions.

This thesis aims to provide novel insights and methods to aid in the difficult task of finding good solutions to urgent and complex environmental problems.

Judgment and values influence choices under uncertainty

Despite the challenges of wicked problem contexts, public and political societal debates frequently raise the expectation that science should be able to provide specific and unambiguous guidance for handling pressing problems in health, the economy or the environment. However, one of the most critical insights of decision science is that all decisions are based on the inherent values of the decision-maker (Keeney 1992). Therefore, objectively "right" or "wrong" decisions are hard to find in complex problem contexts with competing objectives and values, and high uncertainty (Keeney 1992; Bond et al. 2008). In the absence of clear and certain solutions and contested criteria by which to determine what is best, judgments and values become inevitable elements of decision-making. While values are an encapsulation of beliefs about the relative worth or importance of something, judgments are the internal guide when faced with choices based on all available conscious or unconscious information, which includes information on all values that are part of the decision context (Keeney 1992). When judgments are made, there tend to be both random variance and bias (Kahneman et al. 2021), adding uncertainty to inherently difficult problem contexts. One of the reasons might lie in the challenge to identify, understand and articulate even one's own values, which might facilitate decision-makers reliance on heuristics and other shortcuts (Kahneman 2012; Marewski et al. 2010; Bond et al. 2008). Judgment and values in decision making are not only relevant in the final choice among options but can be found at all stages of the decision-making process. Decision theory is a vast field of science that encompasses many different concepts and models, including much work on decisions under uncertainty (Gigerenzer and Gaissmaier 2011; Tversky and Kahneman 1974). While this thesis won't commit to one specific method or concept, such as bounded rationality, expected utility theory, or rational choice theory, to name just a few, the focus was set on the two specific aspects of values and judgments as they play a role across most concepts, and are particularly important in complex environmental problem contexts (Gigerenzer and Goldstein 1996; Kahneman 2003; Rabin 2000; Linkov et al. 2006; Baron 1997).

Unaided judgments depend considerably on the intuitive and rational reaction of the human mind to different types of uncertainty (Regan et al. 2005; Robin Gregory et al. 2006; Huang et al. 2011; Polasky et al. 2011; Cinner 2018; Tversky and Kahneman 1974). How humans process information and make judgments is influenced by context on content (Slovic et al. 1990). The interaction of the human mind with available information is influenced by the way the information is presented and how communication is structured and facilitated. This affects both the rational processing and the emotional response when being exposed to any kind of information. Emotive reaction and rational thinking are in constant interaction when the human mind is active (Finucane et al. 2003). Among the many identified psychological biases (Cinner 2018; Glynn et al. 2017; Tversky and Kahneman 1974), the importance of emotional response to information has become known as the "affect heuristic" (Finucane et al. 2000). Intuitive personal preferences for available choices are most often constructed or influenced through the deliberations and interactions during the decision process (Slovic 2006; Kellon and Arvai 2011).

In the context of wicked environmental problems with their many uncertainties and lack of complete understanding of causes and effects, decision-makers are faced with multiple and interlinked complex choices with often unknown implications. Judgments are an inevitable part of decision processes. Judgements are intrinsically linked to values and information, which are not necessarily easy to directly access cognitively and often filtered through biases (Cinner 2018;

Hammond et al. 1998; Keeney 2002). The choices within scientific analysis, such as a set of indicator species to define objectives, thresholds to define targets, a set of specific methods of management to compare to each other, the type of analysis to conduct, the choice of which stakeholders to engage with and in which way, all involve judgement in some form, which have to rely on the connection of available information and internal values. In the best case, the judgments that inform these choices are accompanied by a transparent rationale and are based on deliberation and critical thinking, conveying the underlying links between values and information. In the worst case, these judgments are made intuitively without critical reflection on possible alternatives and implications, and the values and information that led to the judgment remain unclear.

Together, these realizations raise the question of how robust processes are that identify solutions to conservation problems. Several aspects in the current applications of conservation science are prone to leading to potentially unreliable or wrong results and general concepts. To prevent choices of suboptimal methods from persisting in science, and wrong conclusions about the state of the world or robust decision making getting perpetuated, several core aspects of a general decision-making process (Figure 1. 1) were examined for potential issues and possible improvements (Smaldino and McElreath 2016). In particular, this thesis explores different ways in which judgment-based choices and underlying values can influence decision-making for nature conservation. Each of the four chapters investigates a different type of implication that choices within different decision-making steps can have on the final decision made, and what possibilities exist to identify and understand these implications and include them in a transparent way in the decision process.

Aspects of decision making for complex problems and the role of judgement

Models of the natural world, including response to management

Choices about which analytical methods and data to use in describing the processes or systems at the heart of a decision problem can profoundly influence decisions. Methodological choices made when modelling trends in a population of a threatened species, the condition of an ecosystem under management scenarios, or the level of genetic inbreeding under a species reintroduction plan have an immense influence on decisions that depend on those analyses (Halpern et al. 2006; Silberzahn et al. 2018; Gelman and Loken 2019). For example, the decision to structure data in a particular way has been shown to have implications for interpreting trajectories of species declines within the IUCN Red List repository, indicating the need for more nuanced measures that are able to capture complexities and interactions between multiple factors when analysing global data (Leung et al. 2020).

Similar effects are reported when trying to understand the effectiveness of alternative management interventions (Hajkowicz 2007; Hajkowicz et al. 2000; Bayraktarov et al. 2019). Efforts to collect information about effectiveness of past actions in order to support evidence-based decisions in similar contexts are widespread but have had limited success (Ferraro and Pattanayak 2006; Law et al. 2017; McIntosh et al. 2018; Rose et al. 2019; Sutherland et al. 2004; 2020). High variability between local ecosystem characteristics in different locations complicates the identification of the most effective interventions (Sutherland et al. 2020).

The insight that choices during data analysis have implications for identifying meaningful patterns and generalizations in conservation science should warrant tests for robustness of results. For example, there is known to be a significant reported bias towards vertebrates in ecology and conservation studies that may limit the generality of ecological findings and their applicability for underpinning management decisions aimed at conserving biodiversity more generally (Di Marco et al. 2017; Wilson et al. 2016). Based on the unfortunate situation that the definition of assumptions that underpin generalizations is still frequently neglected (Spake et al. 2022), I investigated how including different important parameters during analysis impacts the identification of frequency distributions of conservation-relevant parameters in my second chapter. In particular, I compared prevalence patterns within different subgroups of data, including species, geographic location, threats, and management type in a database derived from a structured literature review on conservation decisions around the world.

Strategies to support decision-making

A range of different decision-support tools and frameworks have evolved to help decision-makers navigate a range of different problem contexts (Acosta et al. 2016; Pullin et al. 2016; Stoeckl et al. 2016; Gregory et al. 2012; Schwartz et al. 2018; Bower et al. 2018). Well-known examples include so-called Systematic Conservation Planning (Ball et al. 2009; Margules and Pressey 2000; Moilanen, Wilson, et al. 2009), Structured Decision Making (Gregory et al. 2012), Adaptive Management (Westgate et al. 2013; Walters 1986; Holling 1978), Multi-Criteria Decision Analysis (Adem Esmail and Geneletti 2018; Huang et al. 2011) and Cost-Effectiveness Analysis (Carwardine et al. 2008). The relative value or merit of a given tool or approach depends on the decision context, and there is no single best approach (Game et al. 2014). However, decision science provides basic standards that should be considered as a foundation of any decision-making process involving values, judgements and uncertainty (Gregory et al. 2012; Hammond et al. 1998; Tversky and Kahneman 1974; Kahneman 2012). Most common frameworks recommend dividing the process into distinct steps to facilitate critical thinking on individual aspects and by structuring the complex process into more manageable thematic phases (Figure 1. 1).

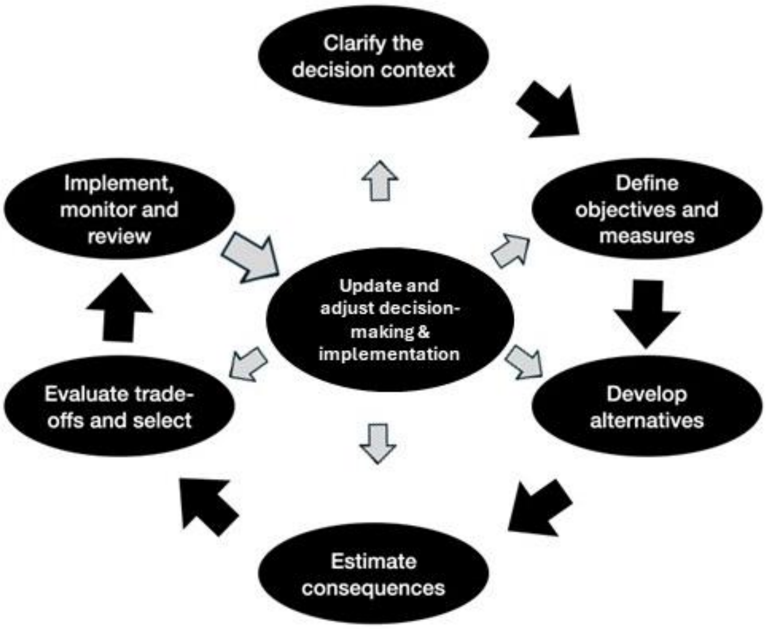


Figure 1. 1: Schematic diagram of individual steps within decision-making processes, starting with the clarification of the decision context, adapted from Gregory et al., 2012. The steps can be revisited multiple times during the planning to refine the decisions and content in each step. The circle can also be re-entered for iIterative decisions with new insights gathered from monitoring after implementation, for example in Adaptive Management contexts.

The choice of an adequate decision-support framework or tool can itself be a difficult decision. Because not all approaches can be explored simultaneously, the decision-maker or involved stakeholders or experts have to use their subjective judgment to make a choice about which one should be used. This choice of decision-support is often predicated by the background and training of the user or lead decision analyst (Gibson et al. 2017) and has been shown to have a bearing on decision outcomes. For example, the techniques used to analyse and rank consequences of different actions have an impact on the ranking of options (Keeney 2002; Hanea et al. 2018; Visconti and Joppa 2015; Margules and Usher 1981; Smith and Theberge 1987).

Many publications present evidence on the impact of modelling choices on priorities and identified best actions (Table 1. 1). However, the potential impact of the choice of decision support approach, including which elements of decision-making (Figure 1. 1) are utlised, has not yet been evaluated in a quantitative way for the field of conservation science and practice. I explore this critical aspect in more depth in chapter 3, where I use a structured literature review to assess how often different decision support frameworks and tools include different decision-making elements. In particular, I assessed the frequency of inclusion of clear, quantifiable objectives, a concept of cause and effect, an assessment of uncertainty, acknowledgement of socio-economic context and deliberation on trade-offs.

Table 1. 1: Examples of studies documenting how the choice of different aspects of decision-making change the outcome or highlight other critical issues. Multiple examples presented here were authored by researchers associated with the Centre of Excellence for Environmental Decisions, a globally well-known hub for conservation planning focused science.

	Documentation of impact on plans or priorities	**References**
Sensitivity to objective setting	Single species presence/absence from a set influences priorities substantially. Authors explored how excluding or including a given species changes spatial priorities in a multi-species prioritization. They develop three metrics to quantify changes in priorities, and explore how these changes depend on the total number of species used in the prioritization, the spatial characteristics of the given species distribution, and how species share their space with other species used in the prioritization. The authors recommend using at least 50 species for regional planning.	(Kujala et al. 2018)
	Robustness of prioritization can tolerate some missing data, but patterns of clustering differed according to whether biotic or abiotic data alone was used or both combined. Author applied a decision support tool for marine protected area design in two regions of British Columbia, Canada, and sequentially excluded the datasets with the most limited geographic distribution. The reserve selection method was robust to some missing datasets. The removal of up to 15 of the most geographically limited datasets did not significantly change the geographic patterns of the importance of areas for conservation. Including abiotic datasets plus at least 12 biotic datasets resulted in a spatial pattern similar to including all available biotic datasets. It was best to combine abiotic and biotic datasets in order to ensure habitats and species were represented.	(Ban 2009)
	Effect of setting/choosing target and objective on systematic conservation planning. The authors examined three types of targets; percentage of landscape, percentage of umbrella species range, and minimum number of sites, to see how the final set (in terms of numbers of sites and percent of land) is affected and how well the final set represents the full suite of mammal species. We found a large discrepancy (164,000 km2) in the land required to achieve minimal representation targets depending on the target used.	(Wiersma and Sleep 2018)
	Effects of social values on plans. The authors determined the effect of the different types of social data on spatial prioritization compared with	(Karimi et al. 2017)

	biological data alone, using a case study in Australia. The type of social data (i.e., conservation opportunities or constraints) significantly affected spatial prioritization outcomes.	
	Review of Ban and Klein 2009 on different types of cost in MPA planning shows how large differences in cost data can be.	(Ban and Klein 2009)
	Effect of integrating other objectives (here: REDD) into prioritisation changes plans	(Venter et al. 2013)
	Suggest increasing relevance of type of objective setting: qualitative objectives, quantitative objectives with no rational (rules of thumbs, general targets), subjective rational (based on ecological insights) or ecological justification (modeled thresholds)	(Magris et al. 2014)
	Spatial plans that meet targets for biodiversity might get changed through further consulting with stakeholder groups. This happens often without re-assessing how this might compromise the targets	(Mangubhai et al. 2015)
	Thresholds for decisions: 1) biological thresholds that lead to system changes, 2) utility threshold where small changes lead to large changes in outcome, 3) decision thresholds that should prompt specific actions	(Martin et al. 2009)
	On the ground conservation activities from communities are often overlooked in SCP studies and might therefore not depict realistic projections or justifications of proposed planning zones	(Van Vleet et al. 2016)
	Planning of multiple stakeholders in the landscape is likely to play out in different ways. Authors investigated how organizational behavior and conservation outcomes are affected by the presence of autonomous implementing organizations with different objectives, in particular how alternative behaviors (e.g., organizations acting independently or explicitly cooperating) affected an organization's ability to protect their feature of interest. Features with highly correlated spatial distributions, although typically considered an opportunity for mutually beneficial conservation planning, can lead to organizational interactions that result in lower levels of protection. These detrimental outcomes can be avoided by organizations that cooperate when acquiring land. For cooperative purchases to benefit both organizations' objectives, each must forgo the protection of land parcels that they would consider to be of high conservation value.	(Bode et al. 2010)
	Discussion of potential negative consequences of considering economic objectives possibly leading to planning outcomes similar to the opportunistic conservation planning that was conducted before systematic conservation methods.	(Arponen et al. 2010)

Sensitivity to threats / theory of change	Effects of leakage can be avoided when included in planning, but without inclusion, net effect of protected areas can be negative	(Bode et al. 2015; Devillers et al. 2015; Hervé et al. 2016; Renwick et al. 2015)
	Evidence of multiple restoration projects failure due to missing assessment of existing threats	(Bayraktarov et al. 2016)
Sensitivity to quantitative objectives and meaningful metrics	Authors recommend that species specific targets should be based on IUCN red list status to link conservation goals to species' persistence and avoid further declines that are likely to happen when thresholds are not linked to ecologically meaningful quantities.	(Pfab et al. 2011)
Sensitivity to socio-economic context	Effect of protected areas on conservation and development within surrounding land parcels: Using spatiotemporal data sets on land cover and land protection for three sites (western North Carolina, central Massachusetts, and central Arizona), we examined whether the existence of a protected area correlates with an increased rate of nearby land conservation or a decreased rate of nearby land development. At all sites, newly protected conservation areas tended to cluster close to preexisting protected areas. This may imply that the geography of contemporary conservation actions is influenced by past decisions on land protection, often made for reasons far removed from concerns about biodiversity.	(McDonald et al. 2007)
	Establishment of a protected area is increasing land prices in adjacent parcels	(Bode et al. 2010)
	Authors found that average human population growth rates on the borders of 306 PAs in 45 countries in Africa and Latin America were nearly double average rural growth, suggesting that PAs attract, rather than repel, human settlement. Higher population growth on PA edges is evident across ecoregions, countries, and continents and is correlated positively with international donor investment in national conservation programs and an index of park-related funding. These findings provide insight on the value of PAs for local people, but also highlight a looming threat to PA effectiveness and biodiversity conservation.	(Wittemyer et al. 2008)
Sensitivity of results to data	Impact of species mobility for spatial priorities. Incorporating the temporal dynamics of species into spatial prioritization substantially changes the spatial pattern of conservation investment, increasing the overall area needed to be placed under conservation measures to achieve a specific target level of species protection. Targeting bottlenecks, locations critical to each species when its distribution is at a minimum, prioritizes a very different suite of sites to those chosen using the traditional approach of static distribution maps based on occurrences pooled across time.	(Runge et al. 2016)

	Impact of cost proxies on prioritisation and conservation action Authors tested how sensitive prioritizations could be to differences in the spatial grain of cost data by demonstrating how the conclusion of a classic debate in conservation planning between cost and benefit targeting was altered based on the available information. Authors recommend to look for proper cost estimates on the resolution of the decision, unless working on very large scales where more detailed cost estimates are not feasible.	(Sutton et al. 2016)
	Availability of philanthropic funds influence conservation spending on PA establishment more than biodiversity data.	(Larson et al. 2016)
	Authors demonstrate impact of spatial grain of cost and biodiversity data in example of TNC investment in Virginia. They found the apparent effectiveness of cost and benefit targeting depended on the spatial grain of the data used when prioritizing parcels based on local species richness. However, when accounting for complementarity, benefit targeting consistently was more efficient than a cost targeting strategy regardless of the spatial grain of the data involved. More pertinently for other studies, we found that combining data collected over different spatial grains inflated the apparent effectiveness of a cost targeting strategy and led to overestimation of the efficiency gain offered by adopting a more integrative return-on-investment approach.	(Sutton and Armsworth 2014)
	The authors compared nine scenarios of opportunity cost by calculating the area and cost required to meet our targets. They further compared spatial priorities with those that are considered consensus areas by several proposed prioritization schemes in the Mediterranean Sea, none of which explicitly considers cost. Results show that area is a poor cost surrogate and that the most effective surrogates are those that account for multiple sectors or stakeholders.	(Mazor et al. 2014)
Sensitivity to models and technical settings	Authors examine the effect of spatial scale on conservation planning and found that the probability of adequately representing an unmapped species in a protected area system will be low unless the total fraction of the region being protected is larger than the species representation target.	(Kendall et al. 2015)
	Authors measure the extent to which changing planning unit shape, size and baseline affects the results of conservation planning assessments. They show that using hexagonal planning units instead of squares produces more efficient and less fragmented portfolios and that using larger sizes produce portfolios that are less efficient but more likely to identify the same priority areas. Using real-world constraints in the analysis, based on reducing socio-economic costs and minimising fragmentation levels, reduces the influence of planning unit characteristics on the results.	(Nhancale and Smith 2011)
	The choice of planning mode has relevant implicit consequences. Results show big differences between minimum set, maximum coverage and max utility planning. Some biodiversity features can end up with targets that are very expensive to satisfy thus reducing resources available for other, possibly more worthy conservation causes.	(Moilanen and Arponen 2011)

Sensitivity to targets	Authors test sensitivity of results to quantity and quality of data when using species-area-relationships (SAR) to define targets. Habitat targets based on the SAR can be strongly influenced by sample size, choice of richness estimator and the level of habitat classification.	(Metcalfe et al. 2013)
	The way targets are organized (e.g., individual targets for many species, or other metrics of biodiversity) influences the calculated ROI.	(Laitila and Moilanen 2012)
	Authors compare different target setting methods: target based, core area, and additive benefit. compared target-based planning to alternative approaches, such as maximum-utility planning, which can operate without the specification of strict targets. We found that target-based planning retained on average a significantly lower fraction of the distributions of all biodiversity features than did alternative methods. This sub-optimality fundamentally follows from the nestedness of species distributions being ignored in target setting, leading to investment in features that occur in relatively species-poor and expensive areas. Consequently, benefit-based alternatives to target-based planning will achieve higher overall conservation performance.	(Di Minin and Moilanen 2012)
	Treating all species equally puts strong emphasis on the conservation of widespread features. Given that these are often species or habitats of low conservation priority, use of this type of target may cause the misplacement of conservation investment. Authors recommend assessing and using priorities associated with different biodiversity features to define differential targets, based on the type of biodiversity goal and the data availability. Ideally, representation targets should be used to ensure long-term persistence of features, such as the minimum viable area or population size.	(Vimal et al. 2011)

The psychology of decision-making

Decision making, and the way humans think when they are faced with choices, has been at the focus of psychological studies for decades, and has produced a range of sometimes contradictive theories, with several schools of thought engaged in ongoing discussions (Gigerenzer 2025b). The key differences in the assumptions about human though processes lie in the characteristics of the assumed decision contexts. Earlier theories assumed the people act rationally, and diversion from rational decision making are an exception, for example, in maximum utility theory. However, this assumption roots in the belief that the decision maker can calculate all expected outcomes of the decision with low or no uncertainty, and that emotions do not play an important role. Despite clear statements in the developed theory that these conditions cannot be expected in general, the theory has led to the development of the many economic models applied in the world to this day. The study of biases and irrationality has confirmed and broadened the insight that most people do not act according to rational logic in many circumstances (Tversky and Kahneman 1974). A range of well-studied psychological effects take place during information processing and decision-making, leading to cognitive biases that can influence decisions in potentially negative ways (Kynn 2007; Glynn et al. 2017; Cinner 2018; Tversky and Kahneman 1974; Kahneman and Klein 2009). These biases include, for example, confirmation bias (giving preference to information that confirms ones views), anchoring (being influenced by information that comes up early), loss aversion (feeling that losses weigh more than gains), affect heuristic (being influenced by current emotions), availability bias (giving recent memories more weight), choice overload (difficulties deciding between too many options), commitment bias (sticking to past beliefs even when it turns out they were not good), or the sunk-cost-trap (keep investing into something that would be rational to give up). Therefore, a range of interventions during human interactions and individual thinking have been developed to counteract unwanted psychological effects in different settings. A third school of thought focused on the importance of the problem context and circumstances that determine the level of uncertainty in the decision, and options to come to good decisions by reducing the problem to a more manageable complexity, the so-called bounded rationality, or small world problems, in which many of the discovered biases can play a functional role (Gigerenzer and Goldstein 1996; Kahneman 2003). In summary, it is important to consider the context of the decision making and the expected level of uncertainty, before applying assumptions on cognitive processes to create a rigorous planning process with meaningful methods.

Impact of all three types of models can be found in conservation planning and environmental sciences. For example, utility maximization is at the core of many optimization models, which are frequently used in parallel to heuristic approaches in systematic conservation planning software (Gurobi Optimization 2024; Ball and

Possingham 2000; Moilanen et al. 2014; Hanson et al. 2019). Especially in the context of wicked problems, nuances in the problem context should determine the choice of most suitable analysis methods, and determine expectation of rational or irrational behavior of involved stakeholders or scientists. For example, it is likely more appropriate to apply heuristics instead of utility maximization under the high uncertainty or lack of available data, while in contexts with good data availability and options to apply scenario analysis, the use of heuristics might deliver suboptimal results compared to optimization approaches (Gigerenzer 2025b).

Most common applications from the research on cognitive biases can be found in expert elicitation procedures, where groups of experts estimate quantities or probabilities in the absence of available data in support of decision-making, or different views and priorities are elicited from different stakeholders in society (Turoff 1970; Novakowski and Wellar 2008; Canessa et al. 2022; Hanea et al. 2017; Speirs-Bridge et al. 2010; Hemming et al. 2018; Martin et al. 2012). While a range of publications exist that focus on group-effects and mitigation options that improve the accuracy or reliability of estimated quantitative data the conservation science, other standard tasks that produce qualitative types of information in this field have been rarely explored for the effect of bias, error and reliability. This is despite the use of similar practices in qualitative elicitation procedures, such as for example policy Delphi processes, that do not aim at consensus, but on identifying, exploring and understanding the breadth of valid and relevant possible opinions and interpretations across a group of individuals and their underlying assumptions (Canessa et al. 2022; de Loë and Wojtanowski 2001; Novakowski and Wellar 2008; Turoff 1970).

Classification of information from free-flowing text into categorical data provides the basis for many scientific analyses, especially in structured or quantitative literature reviews. The citation report from Reuters Web of Science for systematic or literature reviews in the field of ecology and conservation shows a steady increase of reviews with an average citation rate of 76 and an h-index of 326 as of

June 2021, restricted to reviews and journals with focus on biology and ecology and based on the search terms “systematic review” OR “literature review” AND “ecology” OR “conservation”. Citation rates are used as a measure of impact of science, and as reviews are rarely replicated but are on average more than twice as often cited as other publications, unreliable information might arrive at the forefront of available information that can become influential in science and policy. To provide safeguards for quality, best-practice guidance documents exist to navigate researchers through data collection regarding the selection of publications from larger collections (Moher et al. 2009; Pullin and Stewart 2006). While these standards account for the importance of repeatability and inter-rater-reliability, there is no information on how to best combine information from multiple experts or raters, despite multiple options, including mathematical and behavioural aggregation (Clemen and Winkler 1999). Both have advantages and disadvantages, and different contexts can benefit from a combination, While individual rating followed by mathematical aggregation have become an accepted standard procedure to assess reliability of ratings (Marry L. McHugh 2012; Marcoci et al. 2019), the impact of group versus individual rating of selected texts has not been acknowledged sufficiently in the inter-rater reliability literature, despite evidence of a profound influence on the results within expert elicitation and other scientific fields (Levine et al. 1998). In addition, existing protocols to investigate differences between individual and group-based decision-making highlight the importance of parallel rating, and exposure of individual choices to critical review through others (de Loë and Wojtanowski 2001; Mukherjee et al. 2016; Turoff 1970). To contribute to the knowledge about of the effect that group discussions can have on the understanding and classification of free-flowing text, I dedicated the fourth chapter to an experiment in which I measured the frequency of errors, agreements and disagreements between individual rating before and after group discussions.

Integrating understanding of the natural world and socio-economic context into decision processes

Decision-making requires the integration of facts and human values. Facts include insights of high certainty from science about how the world works, and predictions on how alternative actions would impact the socio-ecological system encompassing the natural world and human societies, that are considered of high certainty. Values include goals and motivation of decision-makers and stakeholders that determine subjective preferences. Good decision-making requires a framework that facilitates the combination of best knowledge on both components to inform deliberation on the priorities and preferences for different outcomes, which can also encompass competing objectives (Robin Gregory et al. 2006; Keeney 1992). The higher the uncertainty in information around facts and predictions, the more assumptions have to be made, which introduce judgments and beliefs, which can be influenced by psychological bias as well as personal values (Tversky and Kahneman 1974).

The most important values to include in a decision process can be hard to identify, because they often only emerge when the problem context and consequences of different solution options, and views of different stakeholders, are well understood (Bond et al. 2008). This results in a complex feedback loop between knowledge systems, problem context, and stakeholder priorities based on their values.

In both system components (facts and values), decision-makers must make choices and judgments. For example, the complexity of cause-effect dynamics is uncertain, and their importance depends on the socio-ecological context. Consequently, decision-makers have to make judgment-based choices about natural and social components of their socio-ecological systems (Rounsevell et al. 2021).

A helpful decision support framework should assist decision-makers to disentangle the two components (facts and values) as much as possible and facilitate a rational deliberation on the most important choices during the decision-making in each. Many studies document the effect of different choices during decision-making (Table 1. 1). However, exploring the consequences of different choices during the decision-making on important trade-offs has yet to become a standard in applied conservation decision-making. While multi-criteria decision analysis is a well-established and widely used method to plan under multiple objectives, it not only can require sophisticated mathematical calculations, but the method can also easily suffer from the unfortunately common approach to score, sum, and rank quantitative results for different objectives, which loses important levels of detail necessary to make informed choices (Game et al. 2013; Adem Esmail and Geneletti 2018; Okolie et al. 2023; Liu and Du 2020). Among the available decision-support frameworks that have been widely applied in conservation, Structured Decision Making (Gregory et al. 2012) pays the most attention to trade-offs and clear articulation of values. I explored how this particular framework can improve the prioritization of candidate management actions given different values.

Thesis structure

The purpose of this thesis is to explore how different choices made during decision-making processes influence conservation management. I seek to contribute to the understanding and improvement of current decision-making practices through the investigation of:

I) The impact of judgment-based choices during analysis

II) The impact of judgments in planning

III) The impact of judgments about data collection, and

IV) A case study demonstrating how the use of a decision support framework can illuminate the impact of different choices during decision-making.

In the second chapter, I expand the understanding of problem context for conservation decisions. I investigate how choices in defining the problem context can influence the identification of relative prevalence of taxonomic groups and the problems which are believed to arise for applied and theoretical conservation. I investigated if general frequency distributions and specific biases described in the general conservation literature exist in the more specific context of conservation decision-making.

In the third chapter, I expand the understanding of the use of decision-support frameworks for different conservation contexts. I used a structured literature review to evaluate how frequently important elements of decision-making were documented in decision processes about conservation management actions across five of the most common decision-support frameworks and tools in conservation planning.

In the fourth chapter, I explore bias in the common task of classifying written content from qualitative text for the purpose of analysis. I used the data I produced in my literature review (Chapters 2 & 3) to evaluate uncertainty in data from literature reviews. Reviews are often used to produce data through coding, and the task of classifying qualitative text most often includes aspects of subjective judgment. I developed a novel way to assess the reliability and validity of qualitative data sourced from a literature review that has the potential to make inter-rater-reliability testing more feasible and informative.

In the fifth chapter, I explore the influence of multiple judgments during decision-making and how they can be assessed and integrated in a transparent and informative way. I used a case study of the dispersal trajectories of plastic debris from different source points along the coast of South Asia to highlight how

Structured Decision Making can clarify and integrate values behind multiple objectives.

In the sixth chapter, I discuss and synthesize how this thesis contributes to improved application of decision-support approaches in conservation science. I revisit insights into the impact of judgment-based choices during phases of the decision process and how my findings fit into the broader literature on uncertainty, judgment, and decision-making.

As all chapters were developed as manuscripts for submission and publication in peer-reviewed journals with my supervisors as co-authors, I have used "we" as a pronoun when describing the work. The preface outlines in more detail which tasks my supervisors and others contributed to.

Chapter 2

Taxonomy and geographic location in ten years of literature on decision-making for conservation

Abstract

Systematic decision processes guide the prioritization of investment into management efforts and implementation. Peer-reviewed publications on management decisions act as a knowledge base for past and current efforts as well as guidance for future decisions. As many species and habitats face growing pressures, it is worth documenting where conservation science focuses its efforts. Here, we analyzed patterns in the prevalence of taxonomic groups and geographic locations in publications describing decision-making processes in conservation across a range of study contexts. We only found similar numbers across the management strategies threat abatement, restoration, protected area planning, and population management in North America. For Asia, Latin America and Africa, more than 75% of examples were about protected area planning, providing limited insight into the full range of strategies. Focus on ten different threats varied across geographic zones, with 20% of examples lacking a clear description, and take, problematic species and loss of habitat most frequently addressed. Despite higher numbers of vertebrates in 35% of all publications, compared to plants (24%), other fauna (16%), systems (12%), and insufficiently described biodiversity (13%), consistent patterns in the types of taxa were weak apart an overall focus on vertebrates across all contexts in North America, and a stronger focus on flora in Latin America. Across all geographic zones, there was no general dominance of vertebrates across any threat category, and only population management mainly focused on vertebrates. Our results highlight a strong prevalence of terrestrial biodiversity (60% of examples) with gaps in freshwater conservation in Latin America and Africa, and marine conservation in Latin America and Asia. Almost 50% of the examples were from Australia and the United States of America, with no examples found for many Eastern European and African countries, and only 26% of applied studies in Asia, Africa, Europe and Latin America.

Introduction

Past and current conservation strategies to slow, halt or reverse the decline of biodiversity during the current extinction crisis have shown mixed results (Ceballos et al. 2020; Leclère et al. 2020; Tittensor et al. 2014). To improve management effectiveness, a small set of studies seek to understand what type of management is applied to specific problems and which circumstances and strategies lead to the desired positive outcomes or failure for species and ecosystems (Pullin and Knight 2001; Sutherland et al. 2004). While repositories that document implemented management actions exist (Sutherland et al. 2020; Sutherland and Wordley 2018), a structured review of the type of decision problems that exist and the way they are tackled does not.

Decision support frameworks and methods use structured, strategic thinking to identify promising solutions to complex problems (Gregory et al. 2012). Such approaches usually include defining the problem and objectives for acceptable solutions, identifying alternative actions or options for solving a problem, and selecting the best option based on the evaluation of collected information against some measure of the stated objectives (sometimes called an objective function). Some decision support processes may make more sense or be more effective in a particular context. For example, some conservation decisions must be made opportunistically, indicating a lack of time for detailed multi-stakeholder consultations or the comprehensive testing or evaluation of alternative actions (Game et al. 2011; Pressey and Bottrill 2008). Hence, it is useful to understand in which contexts decision support and structuring processes are used and how often they support implementation in applied settings.

Reported biases in the focus of ecological research and conservation literature and available data (Clark and May 2002; Di Marco et al. 2017; Meyer et al. 2016; Wilson et al. 2016) prompt the question of how widely different decision support approaches are utilized across a suite of decision contexts, and whether similar distribution patterns of taxonomy and geography exist. A targeted review of systematic decision processes and problem contexts can improve knowledge about current trends in conservation. However, conservation problems are often specific to local conditions, social context, and the desired outcomes or aspirations that people have for a region (Leung et al. 2020; Soule 1985). For a review of the conservation approaches applied within different contexts to have generality, it is essential to document the stated objectives of management and the types of management occurring, and other dimensions of decision context (Acosta et al. 2016).

Here we investigate whether distribution patterns observed in conservation literature persist in the subset of that literature that deals specifically with conservation decision-making. The most commonly observed publication biases in ecology and conservation literature (Clark and May 2002; Di Marco et al. 2017; Meyer et al. 2016; Wilson et al. 2016) were described based on found distribution patterns of taxonomy and geography. Therefore, we focused in our classification on taxonomy and geography but included important covariates such as realm, type of threat and management type. Our structured literature review included 466 examples of conservation decision processes drawn from the Web of Science (Beher et al. 2024).

Methods

We systematically searched published literature to produce a sample of published studies that documented decision processes regarding conservation management actions to address an existing problem. Our goal was to identify publications that described details of decision-making processes that selected a particular management strategy out of a range of options. To be considered, publications needed to contain enough detail to make judgments on the problem context and the frameworks used to support decisions. We adapted a systematic review protocol (Moher et al. 2009; Page et al. 2021) to identify literature published in the decade between 2009 and 2018 from the Reuters Web of Science core collection and produced summary statistics on extracted categorical data (Table 2. 2). In contrast to a systematic literature review, we did not aim to produce a fully comprehensive set of all existing relevant examples to assess measures of effectiveness. However, we still aimed to apply a structured and repeatable process to produce a large sample of examples across relevant variables, including taxonomic, geographic, and conservation planning-related parameters, to provide a first overview of general trends across different characteristics. While our method falls short of the standards of a full systematic review, the terminology and related standards of different types of literature review are complex, and different types can be mixed (Pullin and Stewart 2006; Grant and Booth 2009). Our methods might be most similar to the type of a "systemised review" in Grant et al. (2009), but due to the structured search term and coding with a focus on repeatability and transparency, we refer to our method as "structured" review to indicate that structured methods were used. Accordingly, we developed keywords for the literature search to achieve a feasible balance of sensitivity (getting all information of relevance) and specificity (the proportion of relevant hits).

We conducted our search in December 2018, using the term "decision-making" combined with five common decision-aiding and prioritization methods, under the assumption that the combination of the most commonly applied prioritization methods, in combination with the keywords of "decision-making", would return a large sample of relevant but diverse examples of planning processes (Bower et al. 2018; Schwartz et al. 2018) (Table 2. 1).

Table 2. 1: Key words of the scoping literature search in Web of Science. A post-hoc search was conducted for several keywords that were suggested to be of importance during the review process, however, not enough relevant publications were found to add more examples.

Search stage	**Key words**
First stage	[[“decision-making” OR “decision making”] AND [“conserv*” OR “enviro*” OR “biodiv*” OR “ecolog*”]]
Second stage	1 [“Structured Decision Making”] 2 [“Systematic Conservation Planning”] 3 [“Multi-criteria Decision Analysis” OR “Multi Criteria Decision Analysis” OR “MCDA”] 4 [“Adaptive Management”] 5 [“Cost-effective* prioritization” OR “cost effective* prioritization” OR “cost-effective* prioritisation” OR “cost effective* prioritisation” OR “cost-effective* analysis”] (6 [“Strategic Foresight”] - disregarded) (7 [“Horizon Scanning”] - disregarded)
Third stage	(8 [Open standards for conservation] 1 example) (9 [ProAct] 0 examples) (10 [logically correct reasoning] 0 examples) (11 [commitment to action] 0 examples)

2.1 Data collection

The search returned 7106 publications, which we screened for the presence of conservation-related decision context in the abstract and title (Beher et al. 2024). For the 1218 (17% of search results) publications for which this was the case, we read the full publication. We found adequate details about a decision process that prioritized management strategies for 466 examples (6.5% of search results) and extracted information on several categories (Table 2. 2, Supplementary Table S2.2). If a single publication gave examples of multiple decisions, each individual decision was recorded as one example. If case studies were referenced with citation, they were excluded to avoid redundancy. All code and data for producing shown figures are available on figshare [https://doi.org/10.6084/m9.figshare.26355901.v1]. Measures were taken to improve the clarity of categories and measure noise in the data classification including parallel rating of a subset of publications and group discussions (Supplementary Material S2.1). As a result, some categories were regrouped or collapsed (Table 2. 2). Examples that were not possible to assign to a geographic zone were excluded from the analysis.

Table 2. 2: Collected information for each decision example and collapsing of categories after evaluation of inter-rater reliability.

Category	**Classification**	**Collapsed classification (if applicable)**	**count**
Level of implementation	impl = Implemented (explicitly stated that this was implemented or is about to get implemented) sugg = Suggested (tested/experiment at small scale or calculated **in collaboration** with people who have power to make decision about implementation (but more than just a co-author in the department!)	} Collapsed to application	311
	scia = scientific applied (experiment at small scale **without** collaboration with people who have power to make decision) scit= scientific theoretical (theoretical science / calculated **without** collaboration with people who have power to make decision)	} Collapsed to academic	128
Country	free entry		
Continent	0 = not described/theoretical, Tristan da Cunha archipelago	} excluded	23
	1 = Europe		87
	2 = Americas United States and Canada All other	} collapsed to North America } collapsed to Latin America	136 45
	3 = Africa and middle East	} collapsed to Africa	37
	4 = Asia and Russia and India	} collapsed to Asia	48
	5 = Australia/NZ		86
	6 = other (Azores, Mascarene archipelago, Mediterranean Sea, Seychelles, Western Indian Ocean).	Assigned to zones 1-5 based on closest distance on maps.	7
Type management	0 = not mentioned		2
	1 = spatial prioritization (mostly for protected areas)		238
	2 = population management		65
	3 = threat abatement		115
	4 = restoration		102
	5 = other		30

Type threat (following (Salafsky et al. 2008)	0 = not mentioned		112
	1 = residential/commercial development 2 = agriculture/aquaculture 3 = energy production/mining 4 = transportation/service corridors	1-4 collapsed to LU change and fragmentation	73
	5 = biological and resource use		87
	6 = human intrusion disturbance		16
	7 = natural system modification		57
	8 = invasive/other problematic species		87
	9 = pollution		45
	10 = other		72
	11 = climate change		34
Species / system	0 = not mentioned explicitly (not sure if species, habitat, or other)	0,11,14 collapsed to not described	103
	1 = birds		
	2 = mammals	1,2,4 collapsed to vertebrates	319
	3 = other fauna taxa	3,5 collapsed to other fauna	114
	4 = fish		
	5 = unspecific fauna species		
	6 = one or more individual tree species		
	7 = one or more non-tree individual plant species		
	8 = forest	5,6,7,8,9,12 collapsed to plant	223
	9 = grass/shrub-land		
	10 = coral	10,13 collapsed to system	92
	11 = other (for example geomorphic features, rock/sand, processes)		
	12 = unspecific flora species		
	13 = broad ecotypes or habitat		
	14 = unspecified species (unclear if flora or fauna)		
Realm	0 = not mentioned		2
	t = terrestrial		304
	m = marine		76
	f = freshwater		120
Decision support used	Adaptive Management		106
	Multi-Criteria Decision Making		40
	Cost-Effectiveness Prioritisation		34
	Structured Decision Making		27
	Systematic Conservation Planning		212
	Mix of 2 or more of the above		47

2.2 Summary statistics

We cross-tabulated entries for all categories to create unique individual combinations pairs of attributes for *taxa* and *geographical zone*, *taxa* and *threat*, *taxa* and *type of management*, *taxa* and *realm* and *taxa* and *level of implementation* (Table 2.2), for example, a hypothetical study of population management to regulate harvest rates in Australia that concerns fish and oysters would create two entries for *geographical zone* ("Australia"), *threat* ("take"), *type of management* ("population management"), *realm* ("marine") and *level of implementation* ("academic"), for each of "vertebrates" and "other fauna". Results on the type of decision frameworks used are described in Beher et al (2024, equivalent to chapter 3 in this thesis).

Results

Geographic distribution of studies

We found a similar global distribution of publications on conservation decision processes as was observed in reviews of geographic bias in broader conservation-related science (Wilson et al. 2016) (Figure 2. 1). The spatial (geographic) distribution in published scientific studies maps closely onto the availability of spatial data on species occurrence (Meyer et al. 2016) (Figure 2. 1). A small number of countries were represented in significantly more studies than all others. Locations in the United States of America represented 27% of all case studies, locations in Australia 17%, and locations in China and Brazil represented each 4% of all examples. Complete publication gaps in our review aligned with the countries with the lowest numbers of examples in other reviews (Wilson et al. 2016; Meyer et al. 2016), mainly consisting of locations in Africa, Asia, the Middle East and East Europe. One exception was the higher number of examples in Brazil and China in our review, despite the reported low coverage of available spatial data (Meyer et al. 2016), which may reflect a recent increase in published case studies in those regions.

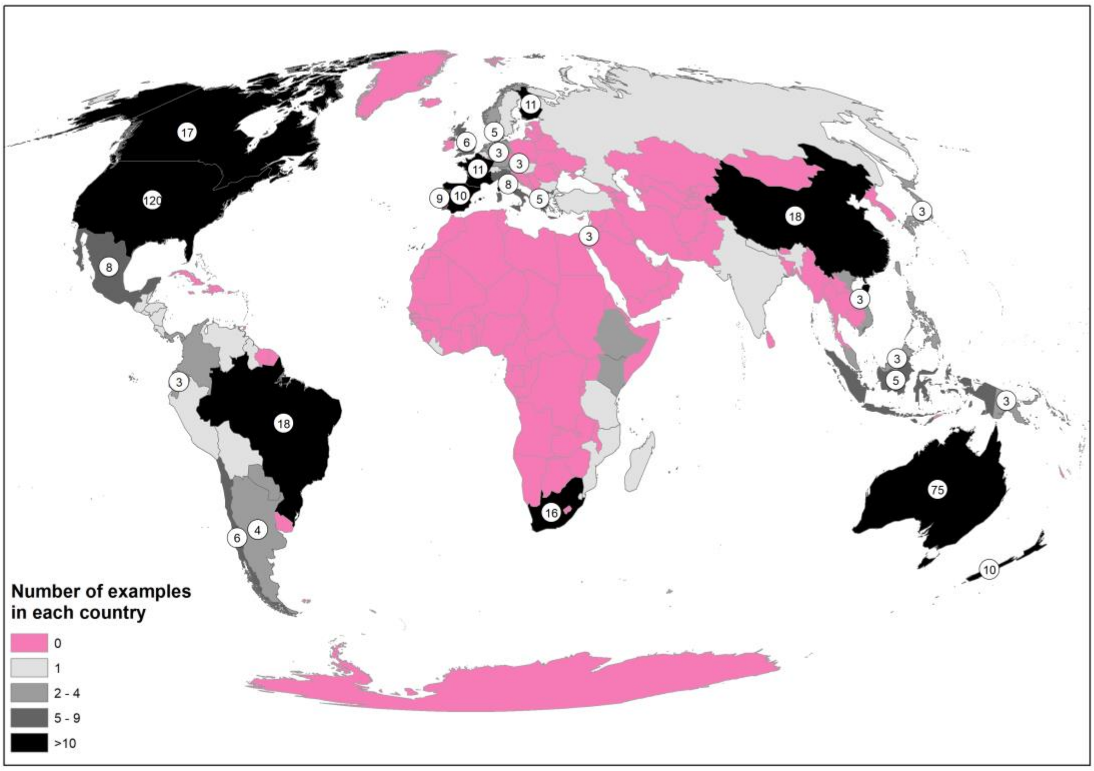


Figure 2. 1: Global distribution of the number of reviewed publications on conservation decision processes and context from each country. Countries with more than three examples are labeled with the exact number.

Taxonomic spread across studies

We found a general trend toward case studies in decision support focused on vertebrates in our sample, which comprised 35% of all publications. Plants were considered in 24% of studies, and other fauna, systems and insufficiently described biodiversity in approximately 16%, 12% and 13% respectively.

Vertebrates were the dominant taxa in case studies in three of the six geographic areas (Figure 2. 2), particularly in North America (> 40%) and Australia (>30%). In Europe, vertebrates were included in more than 20% of all studies, with a smaller difference in numbers to the next frequent taxonomic group than in North America and Australia. The spread of taxa covered by conservation decision studies was more balanced in Africa and Asia, while plants were the most frequent taxonomic group used in decision support studies in Latin America.

Other fauna and systems were in all zones the least frequent taxa, with similar frequency to examples that do not describe any specific taxa. Numbers of examples of taxonomic groups in individual countries are visualized in Summary Material S2.2a.

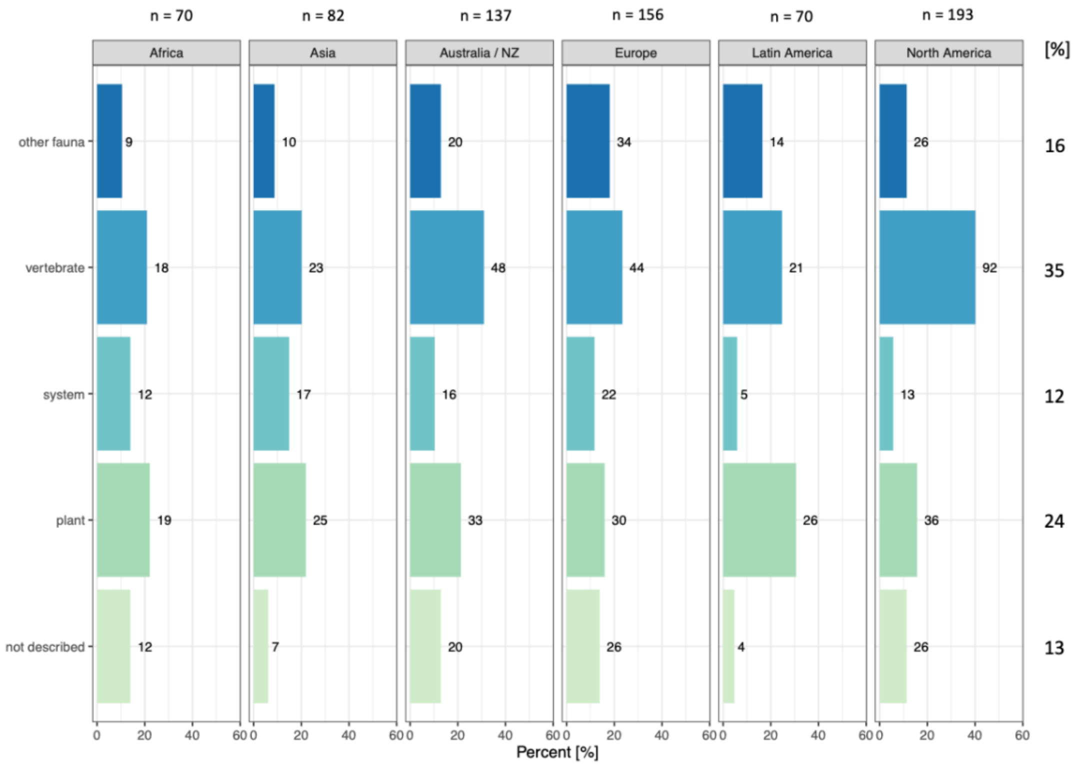


Figure 2. 2: Vertebrates were the subject of the greatest number of conservation decision studies in North America and Australia. Plants were slightly more common in examples of decision processes from Latin America, and the spread of studies across taxa was more balanced in Europe, Africa, and Asia.

Threats

Unfortunately, 112 out of 583 examples did not refer to a specific threat at all, being the most frequently found category (Figure 2. 3). The fraction of examples that do not mention a threat that the management is supposed to address is closer to 10% in North America, but as high as 40% for examples from Europe. The most frequently described threat categories were *take* (87 examples), *problematic species* (87 examples) *and land use change, habitat loss* and *fragmentation* (73 examples). While these three threats were found in similar numbers in general, there were differences between geographic zones. *Problematic species* are mainly found in examples from Australia and North America, while *land use change* and *fragmentation* are relative to other threats more often addressed in Africa and Asia. Examples from Europe show less pronounced differences in the frequency of different threats than all other geographic zones. Threats that are overall less often found can be among the most prominent threats in some geographic zones, such as pollution in Europe and Australia or system change in Australia. Examples addressing climate change are predominantly from North America. A large number of examples (72) were addressing specific threats outside of the used categories.

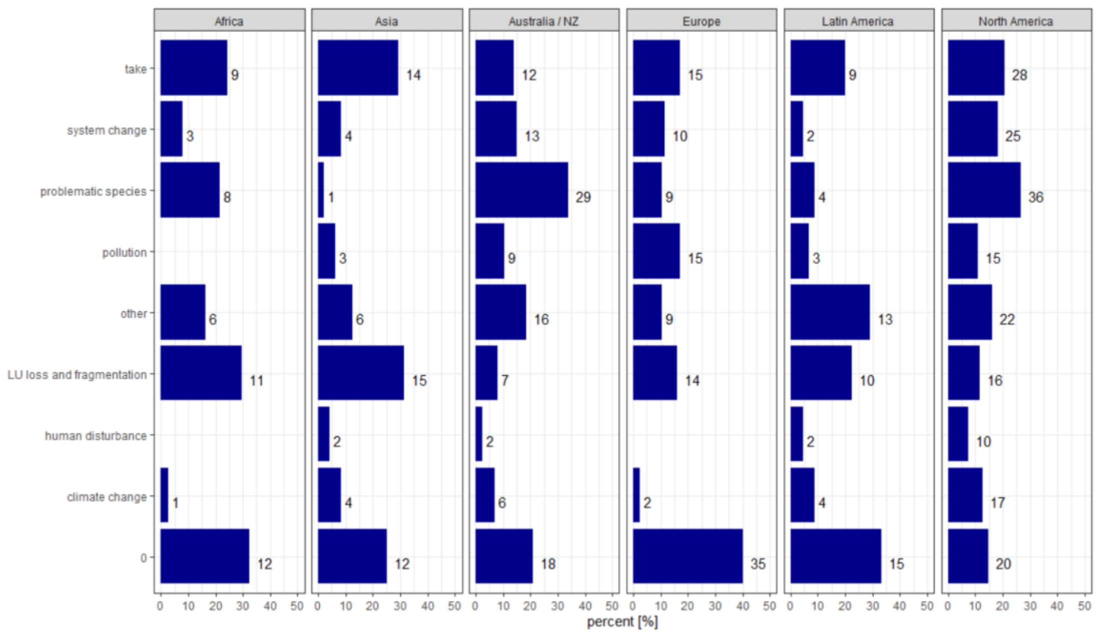


Figure 2. 3: Prevalence of different threat categories in geographic zones. Labels of bars show the count of examples.

Taxonomic groups across types of threat considered

Vertebrates dominated studies of all threat types in North America (Figure 2. 4). Vertebrates were most commonly considered in studies of three threat categories in Australia and Europe, two threat categories in Asia and Africa and one in Latin

America. The taxonomic groups considered with respect to particular threats were mixed across regions, with no particular threat*taxonomic group dominating across regions. This likely reflects the variation in threats and threatened species across different parts of the world. The number of examples of studies addressing *climate change* and *human disturbances* was less than ten in all regions except for North America. Examples of studies addressing *system change and pollution* were also few in Africa, Asia and Latin America (Figure 2. 4). Unsustainable harvest (*take*), *problematic species*, and *land use change* and *habitat fragmentation* were the most commonly addressed threats. Examples that did not document any key threat were the most common study in Europe, Africa, and Australia, and the second most frequent in Latin America. Numbers of examples with each threat in individual countries are visualized in Summary Material S2b.

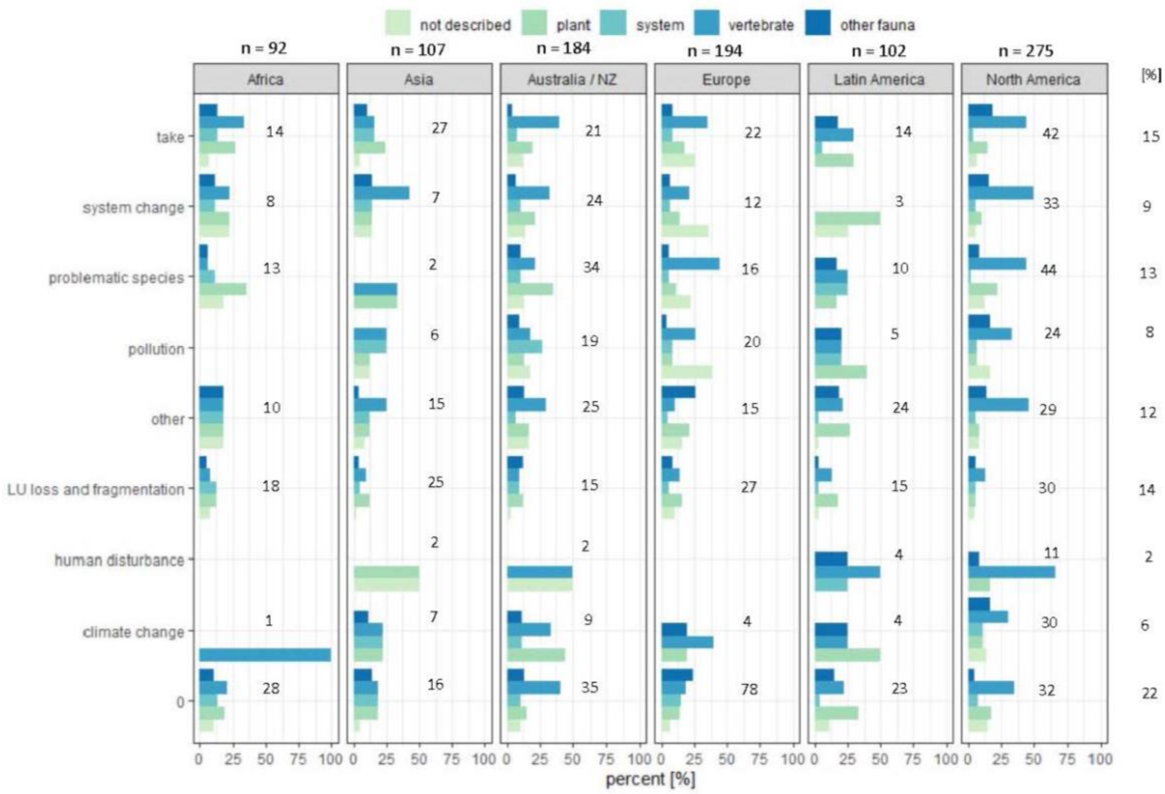


Figure 2. 4: Incidents of different taxa across types of threats. Numbers and percent of each type of threat in each geographic zone in each panel, and the average percentage of each type of threat across all zones and taxa on the right.

Types of management

Protected area design was the most common type of management that was planned for (238 out of 552 examples). *Restoration* and *threat abatement* were the focus of around 100 examples, while *population management* was described in 65 examples. Only 2 examples did not describe what type of management was suggested. In 30 examples, other types of management were included in the decision-making process (Figure 2. 5). While a balanced set of decision-examples across different management types were fond for Australia and North America, examples in all other geographic zones were dominated by planning of protected areas, with over 75% of examples in this category in Latin America, Asia and Africa.

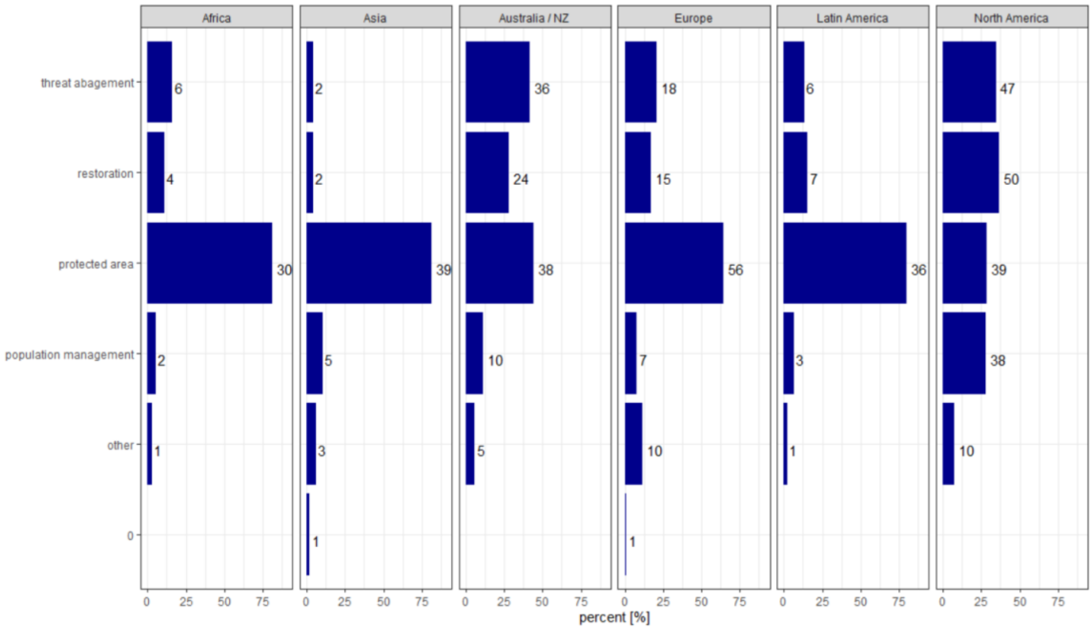


Figure 2. 5: Persistence of management types in examples of decision-making for conservation in different geographic zones. Labels on bars show count of examples.

Taxonomic groups across types of management

We found that examples from North America included vertebrates more often in all four types of management *restoration, protected area planning, population* *management* and *threat abatement* (Figure 2. 6). *Protected area planning* was the most dominant form of management type considered, adding up to more than half of all examples. Interestingly, examples of this type of management exist in similar numbers for all regions, with the majority of examples from Europe. We found only 12 or fewer examples of planning for *threat abatement, restoration* or *population management* for Africa, Asia, Australia/NZ and Latin America. More than half of the examples of these management types were from North America, with a clear dominance of vertebrates. *Population management* was the only management type for which higher numbers of vertebrates was not found in all geographic zones. Numbers of examples of management types in individual countries are visualized in Summary Material S2.2c.

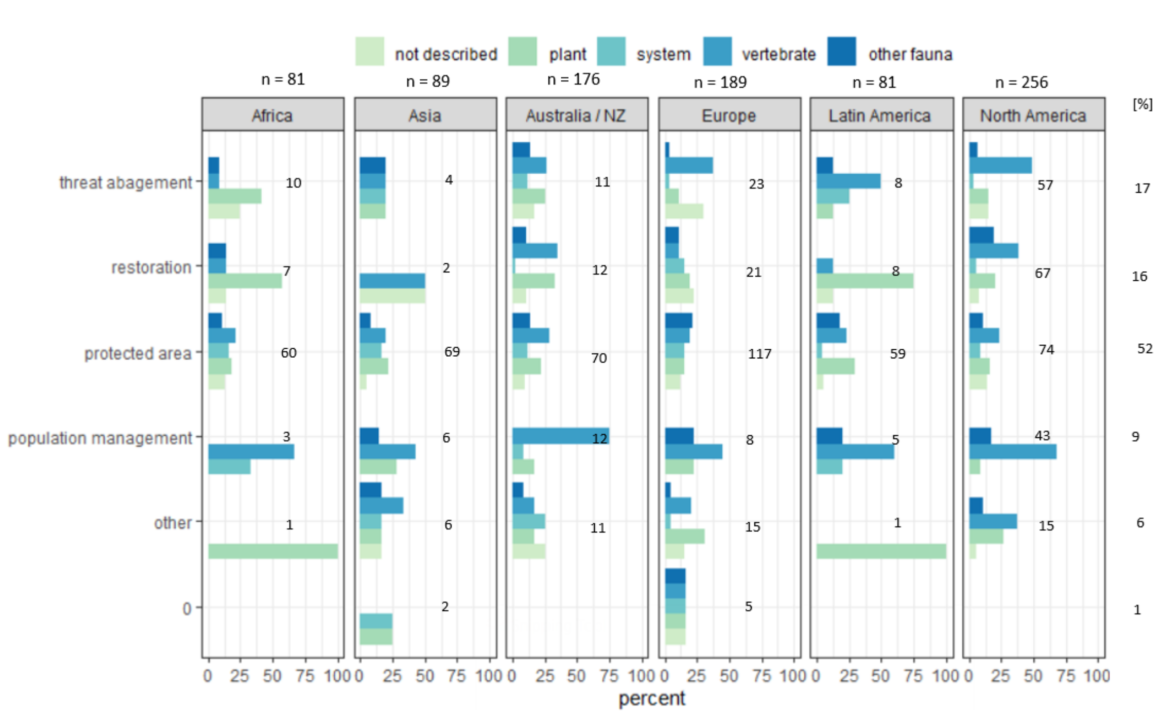


Figure 2. 6: Incidences of different taxa across types of management in the different geopolitical zones. Numbers and percent of each type of management type in each geographic zone in each panel, and the average percentage of each across all zones and taxa on the right.

Taxonomic groups across terrestrial, freshwater and marine realms

Out of 502 distinct examples of decisions for specific realms, 304 were *terrestrial*, 120 *freshwater*, 76 *marine* and 2 not described (Figure 2. 7). We found a clear dominance of vertebrates across terrestrial, marine and freshwater realms in examples from North America, and a smaller dominance of vertebrates in Europe (Figure 2. 7). Only a few examples of marine conservation decision-making were found for Latin America and Africa. Relative to the overall numbers of studies in Australia and New Zealand, relatively few were marine. We found more freshwater examples than marine examples in Africa, Australia/NZ and North America, more marine examples than freshwater examples in Asia, and similar amounts in both realms in Europe and Latin America. Vertebrates were most common in most geographic zones for examples from the freshwater realm Figure 2. 8. We found that only 12% of studies documented decisions across more than one realm.

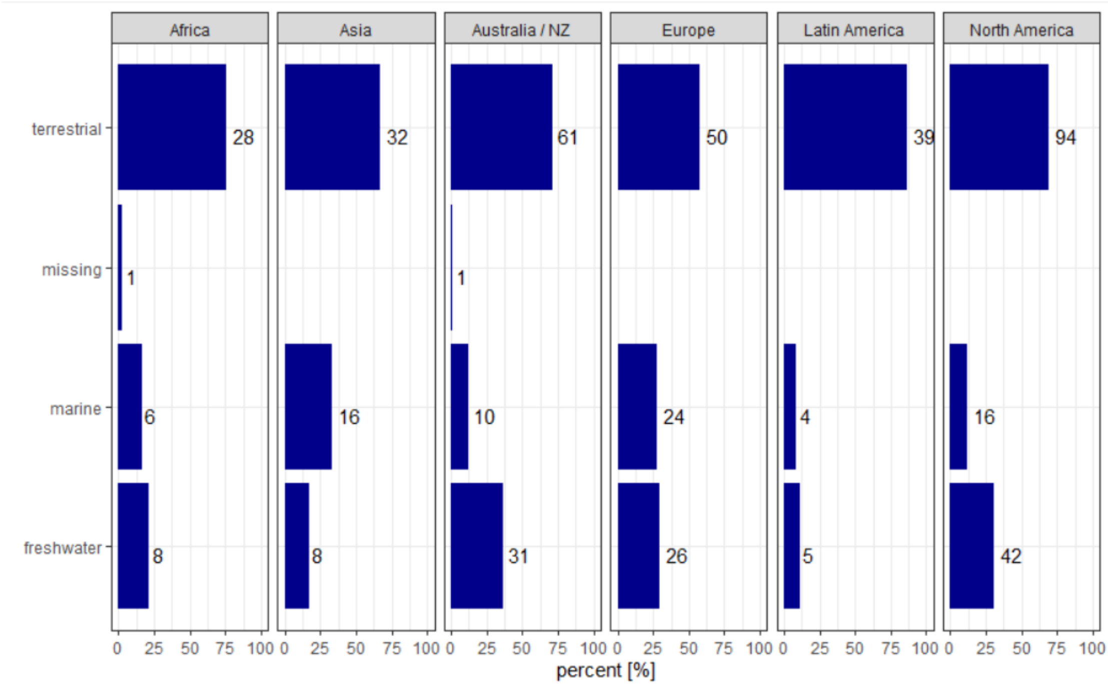


Figure 2. 7: Terrestrial ecosystems dominate in conservation decisions in all geographic zones. Marine and freshwater realms show no clear relative consistent pattern across all geographic zones./

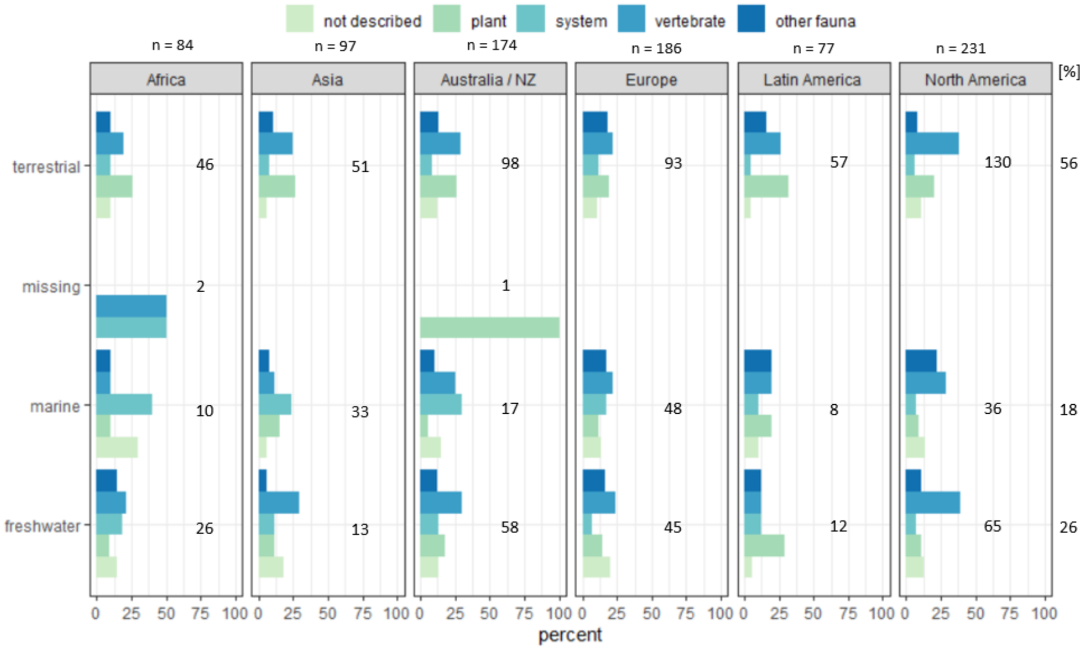


Figure 2. 8: Incidents of taxa across realms with numbers and percent of each realm in each geographic zone in each panel, and the average percentage of each across all zones and taxa on the right.

Taxonomic groups across different levels of implementation

Academic examples of decision making are more common in all geographic zones. We found the largest difference between the two levels of implementation for Latin America, with six times more academic examples than applications, followed by Europe, with five times more academic examples of decisions than documented applications (Figure 2. 9).

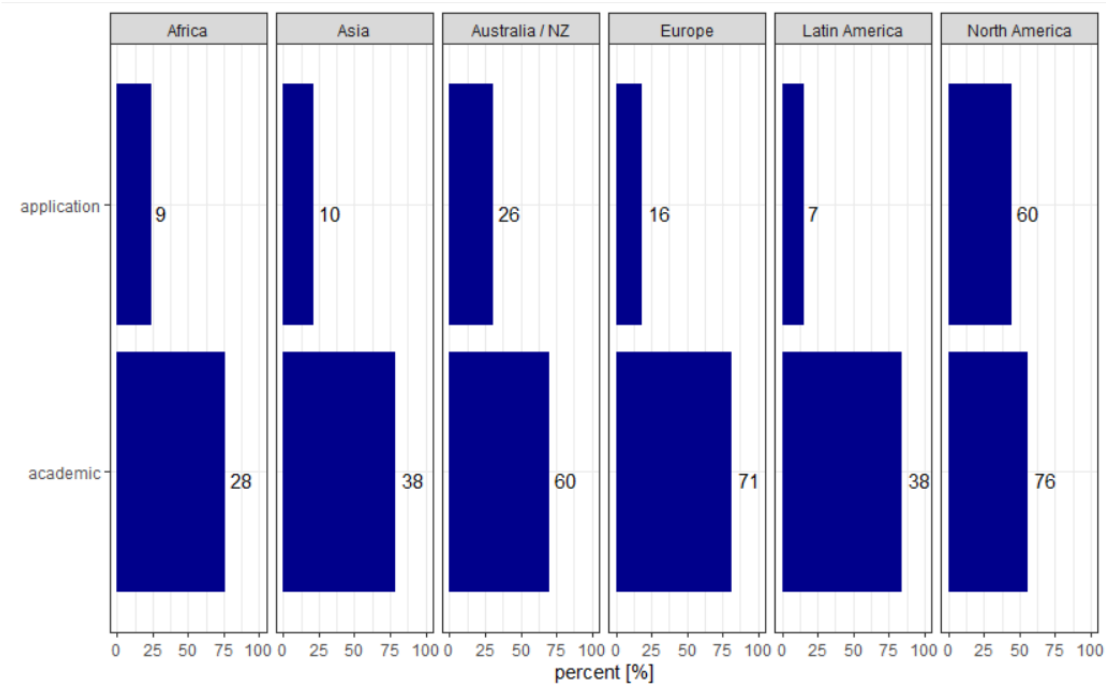


Figure 2. 9: North America is the only geographic zone in which academic examples do not outnumber applications with a large margin.

Vertebrates have only in North America, Europe and Australia higher prevalence than other taxa in both academic and applied contexts. In Latin America, Africa and Asia, plants are more common in academic examples. Asia is the only zone in which vertebrates is not the most common taxonomic group in applied conservation decision contexts (Figure 2. 10).

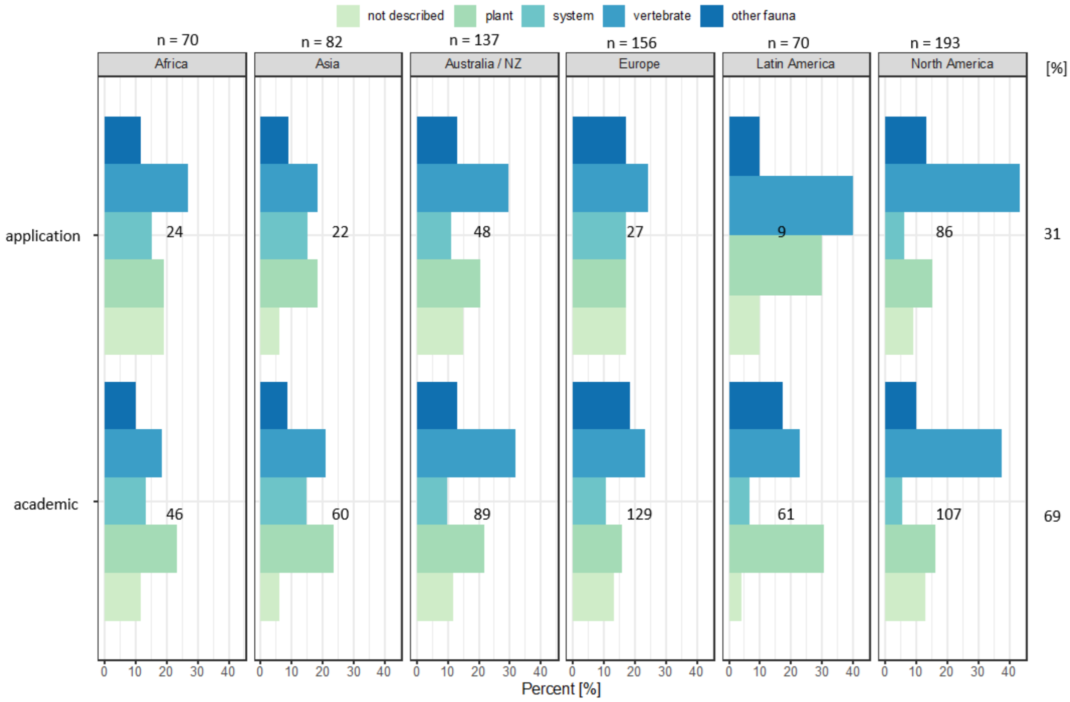


Figure 2. 10: The trend toward vertebrates across academic context of examples and applications. Bars are labeled with numbers of examples that include taxa in objectives, total percent of both categories on the right.

Discussion

Our analysis of documented conservation decision studies showed several strong global patterns regarding taxa and location. We found a clear dominance of studies that document conservation decision processes for vertebrates, with 35% of studies focused on vertebrates among 5 different taxonomic classifications (Figure 2. 1). However, this pattern of taxonomic prevalence is less acute than that observed in the broader ecological literature, which is comprised of approximately 70% of vertebrate focused studies (Clark and May 2002; Di Marco et al. 2017).

Moreover, a strong trend toward vertebrates shows up only in particular places including North America, where vertebrates were the subject of 40% of conservation decision studies across all threats, management types and realms. Vertebrates were the most common taxonomic group in documented applications for decision contexts in all geographic zones except Asia, where a similar number of studies focused on plants. Vertebrates also dominated studies in the freshwater realm in all geographic zones except for Latin America, and were the most commonly targeted taxa for population management across all geographic zones.

We found more publications of conservation decision studies from North America, Australia and Europe in comparison to other parts of the world. The differences were more marked than in similar reviews of the ecology and conservation literature. Our result reflects documented biases in the availability of biodiversity occurrence data, decision support specialists, and overall publication rates (Acosta et al. 2016; Di Marco et al. 2017; Hickisch et al. 2019; Hughes et al. 2021; Wilson et al. 2016).

The impact of taxonomic focus on conservation efforts

A recent study on research bias within terrestrial vertebrates raised concerns about the lack of correlation between the found number of publications and threat status, and strong bias towards very few large-bodied animals (Dos Santos et al. 2020). However, if the skewed distribution of different taxonomic groups in the decision-making related stream of literature is a problematic bias or founded in considerations of conservation need or efficient use of resources would need further analysis. The dominating focus on vertebrate species in the academic and applied decision contexts documented in this study could simply reflect the focus of conservation organisations and governments on umbrella, indicator, iconic and keystone species that are deeply embedded in conservation and ecological thinking . These biases may be exacerbated by technical feasibility for data collection and conservation effort (e.g. detectability during biological surveys) (Gardner et al. 2008; Dos Santos et al. 2020; Mammola, Adamo, et al. 2023; Mammola, Fukushima, et al. 2023). For example, the large collection of implemented management interventions that aim to benefit biodiversity has to date 8870 examples, of which 4549 examples concern vertebrates, which is substantially more than the 35% lead of vertebrates in our study results compared to other examples (University of Cambridge Department of Zoology 2025). A more prominent and problematic focus on animals was found in an assessment of conservation funding in Europe, with concerns about the lack of consideration of habitats and their threat status (Adamo et al. 2022). Threat status was not coded in this study, but might be a worthwhile next step to gain further insight into potential issues.

The focus of conservation effort on mammals may not be a problem per se. However, if the aim of conservation is to protect all of biodiversity, or to protect the biodiversity that brings the greatest ecosystem services, then the preoccupation with mammals may not serve either of those aims. The discussion about the implications of the observed dominance of a particular taxon should consider an assessment of knowledge gaps or a lack of conservation action for other groups of species that may require conservation effort (Clark and May 2002). For example, there is evidence that some taxa, such as insects, are severely underrepresented in the current global extent of protected areas. A more thorough assessment of conservation need when planning for most urgent conservation needs seems, therefore, justified (Chowdhury et al. 2023). However, in our results, examples of all other taxa exist in addition to vertebrates for all geopolitical regions and realms. Therefore, we believe the current documentation of efforts to be rather balanced across the many conservation contexts, and geographic gaps might be a more important issue to tackle.

The absence of published conservation decision studies from some geographic zones, including many countries across Africa and Asia (Figure 2. 1) is likely a significant problem for global conservation efforts that derives from cultural and economic differences. This patterns matches patterns observed in reviews of ecology and conservation science more broadly (Wilson et al. 2016; Di Marco et al. 2017), and one that appears to warrant redress in conservation funding and effort globally, lest critical components of biodiversity will be lost in those locations without any attention, including many of the global biodiversity hotspots.

The strong geographic pattern in published conservation decision science studies that contain more examples from the United States of America, Europe and Australia likely reflects the bias in publications in English-speaking journals when searching the Web of Science. This, in turn, reflects the activity of conservation scientists which aligns with the distribution of wealth and conservation resources. It may be that many conservation decision processes taking place in non-English speaking countries are not well documented in English and hence overlooked by our review. This may result in an overestimate of the geographic bias in conservation science studies toward English-speaking and more wealthy areas. This is an uncertainty that should be explored further, as there is evidence of this problem for the wider field of biodiversity research. For example, 3.4% of our sample was from South Africa, while no examples at all were found for most other African countries. Reporting summarized results for the African continent (in our case 9%) would therefore be an ill-informed attempt to guide conservation. The same is true for the Palearctic, where Europe and China provided most examples, or the Neotropics, where Brazil was the dominant source of examples.

Fortunately, there are clear pathways to reduce some key drivers of geographic bias in conservation decision science studies. Reducing the impact of language and financial barriers to scientists and practitioners from non-English speaking countries is an approach that journals can pursue to reduce publication bias (Burgman et al. 2015). Collaborations with scientists and managers that translate conservation management information into English (Bayraktarov et al. 2020) are efficient and inclusive ways to contribute to a more comprehensive inventory of current conservation efforts (Adams and Mulligan 2003; Garland 2008; Moola and Roth 2019).

To reduce the impact of bias in data availability, novel ways of collecting data could overcome some of the problems of standard data repositories such as OBIS or GBIF, which do not necessarily reflect the real abundance and occurrence of different species. For example, the automated harvest of data from social media has shown large discrepancies between established data repositories and citizen science data, with higher quality data, especially for threatened species (Chowdhury et al. 2022). While issues around accessibility of remote regions or areas of active violence have a large impact on the representation of species in available data repositories, these problems are often harder to control (Hickisch et al. 2019). Strategic improvement of monitoring efforts and investment in sharing available data across all countries will improve our knowledge base of species occurrences and ability to act on urgent conservation challenges.

Reviews of the general ecology and conservation literature have warned that a bias towards vertebrates and certain locations could obstruct conservation outcomes (Boakes et al. 2010; Clark and May 2002; Di Marco et al. 2017; Hughes et al. 2021; Meyer et al. 2016; Wilson et al. 2016). Notwithstanding caveats regarding the availability of published studies in languages other than English in our study, our results indicate that the patterns observed in reviews of ecology and conservation biology persist in conservation decision making literature. However, more nuanced analysis across different contexts shows the inconsistency of this pattern, and the importance of assessing a more detailed context to support interpretation of these results. For example, a higher rate of studies on vertebrates might simply reflect the greater need for planning for vertebrate species, based on legislation, threat concerns, social values, or other relevant factors. If the found patterns are a sign of bias or are patterns based on need will be hard to assess without a detailed analysis of underlying motivations across different countries. This is in line with previous recommendations regarding the transferability and generalization of quantitative ecology data (Spake et al. 2022). The complexity of the interactions between species, threat, locations and management actions have been well documented in the conservation sciences. This underlines the importance of nuanced knowledge when assessing the relevance of global trends in local or regional contexts (Auerbach et al. 2015; Côté et al. 2016; Geary et al. 2019; Haller-Bull and Bode 2019).

The key primary threats that were addressed in the reviewed examples were *Unsustainable Levels of Harvest* (15%), *Land Use Change* (14%), and *Problematic*

Species (13%). Unsustainable Harvest and Land Use change have emerged as dominant threats in other recent reviews (Jaureguiberry et al. 2022; Maxwell et al. 2016). The importance of problematic species and pollution differs in the results of these reviews, with the indication that pollution is more important in aquatic environments, and problematic species in terrestrial environments. This matches the observed pattern in our sample based on a majority of terrestrial examples. A large fraction (22%) of all reviewed studies did not describe a specific threat, indicating a lack of clear focus on problem solving, which has been documented as a key problem in spatial conservation planning (Hermoso et al. 2022).

The representation of different realms in our sample of conservation decision-making publications seems to be more balanced than in the general stream of ecology and conservation literature (Wilson et al. 2016; Di Marco et al. 2017). We noted a comparatively low number of freshwater examples in Asia and Latin America and a low number of marine examples in Australia. Only 12% of the publications reviewed document management decisions for biodiversity across realms, even though many species' lifecycle requires multiple realms and thus do not benefit enough from conservation activities that do not address multiple realms (Beger et al. 2010; Virtanen et al. 2020; Adams et al. 2014; Giakoumi et al. 2019).

The gaps and imbalances we have identified in existing studies of conservation decision processes could be used to guide new academic and applied conservation efforts beyond categories of taxa and locations. Some categories for which a small number of additional examples would already make a big difference would include problematic species and restoration in Asia, pollution, climate change and population management in Africa, marine examples from Africa and Latin America, freshwater examples from Asia and Latin America, applications from Latin America and cross-realm planning in general.

Limitations

We were limited to published, peer-reviewed literature because of the data available to us in form of a central, searchable depository (Web of Science) that allowed us to screen a large amount of literature within the time, budget, and staff constraints of a PhD project. Only a third of our samples documented conservation actions that were implemented or planned for in collaboration with decision-making authorities, and almost half of these were from North America, where a strong bias towards vertebrates exists. The high number of academic studies relative to confirmed applied studies reflects a bias in published conservation literature to methodological inquiry over documenting application. However, compared to an earlier assessment of intention for implementation of conservation science studies between 1998 and 2002, we have found a much higher rate of studies that are not purely academic (Knight et al. 2008). If this difference is caused by the focus on decision-making or a change that has happened over time is not possible to assess without further analysis. Our sampling of the peer-reviewed literature provides useful insights into conservation decision-making contexts, but a detailed sample of the 'grey' (non-peer-reviewed) literature may provide some different insights and represents a clear future research priority (Corlett 2011).

Linguistic uncertainty (Regan et al. 2002) can obstruct the sampling of repositories by keyword search. The necessity to use keywords with high specificity to find the most relevant pool of literature to sample within existing time and budget constraints can lead to the exclusion of studies that use different terminology to describe relevant content but overlap significantly with less relevant publications. Many applied decision support studies may not use the term "decision-making", but might describe a decision process with words like "assessment" or "evaluation". However, using these words as alternative keywords would return many publications that assess or evaluate anything but decision processes. While our sample size (400 studies) was large enough to reveal robust patterns, we recognise that relevant studies will have been overlooked. Linguistic uncertainty will continue to be a hurdle to search-term based literature reviews while there is no consensus on the most useful terminology to include. For a more detailed discussion of the representativeness of the sample see Beher et al 2024.

Conclusion

Our analysis provides insights into, and increased understanding of, the current focus of conservation planning and decision-making efforts. Significant but inconsistent (across continents) taxonomic and geographic patterns exist in documented studies of conservation decision-making. A better understanding of the conservation efforts and investments of non-English speaking countries and in the grey literature is urgently needed to help ensure that all threatened taxa and conservation of functioning ecosystems benefit from strategic conservation investment.

Chapter 3

10 years of decision-making for biodiversity conservation actions: A systematic literature review

Abstract

Decision science emphasizes necessary elements required for robust decision-making. By incorporating decision science principles, frameworks and tools, it has been demonstrated that decision-makers can increase the chances of achieving conservation aims. Setting measurable objectives, clearly documenting assumptions about the impact of available actions on a specific threat or problem, explicitly considering constraints, exploring and characterizing uncertainty, and structured deliberation on trade-offs have been identified as key elements of successful decision-making. We quantify the extent to which these five elements were utilized in published examples of decision making in conservation in both academic and conservation practice between 2009 and 2018. We found that less than 50% of identified examples included all five elements, with differences in the degree of decision science applied across five commonly used decision support approaches: adaptive management (AM), systematic conservation planning (SCP), structured decision making (SDM), multi-criteria-decision-analysis and cost-effectiveness analysis. Example applications that utilized the SDM framework were limited in numbers but used on average more than 50% of the five key elements we considered. Although SCP and AM constituted the majority of examples, they were more prevalent in academic studies rather than management applications. SCP and AM examples were widespread in protected area planning, threat abatement and restoration. Strong geographic bias exists in documented conservation activities that deploy all five decision science elements.

Introduction

Despite the substantial effort and investment into the conservation of species and ecosystems, biodiversity loss is accelerating (C. N. Johnson et al. 2017). The list of threatened species keeps growing, with over a million species threatened by extinction, and many species expected to be lost within two decades (Díaz et al. 2019; WWF 2020). Global assessments have identified comparatively few successful management examples that led to the down-listing of species' extinction risk (Bolam et al. 2021; Hoffmann et al. 2010). Most national and international environmental strategies fall short of their nominal targets and many report worsening trajectories for monitored species (McDonald et al. 2015; Secretariat Of The Convention On Biological Diversity 2020; Tittensor et al. 2014). It is not possible to determine to which extent the strategies developed to stem biodiversity decline are flawed or sound, or whether they are implemented at too small a scale or with inadequate resources. If important insights from decision-science are neglected during planning, the risk of failure and the possibility of perverse or unintended consequences increases (Bode et al. 2015; Devillers et al. 2015; Game et al. 2013; Hervé et al. 2016; Renwick et al. 2015). Existing evidence across multiple disciplines including medicine and public policy including environmental policy shows that structured processes based on decision science lead to a better understanding of the problem at hand, sound evaluation of available options and the trade-offs between them (Arvai et al. 2001; Bekker et al. 2003; Herek et al. 1987; Schafer and Crichlow 2002). Principles of decision science have been used to assess other aspects of conservation applications, such as ecological indicators (Watermeyer et al. 2021). Recent publications call for greater attention to be given to fundamental principles in conservation plans to increase the chances of achieving urgently needed conservation outcomes (Adams et al. 2019; Kellon and Arvai 2011; Maron et al. 2021; Rose et al. 2019; Leclère et al. 2020).

Decision support approaches used in conservation

A range of decision support approaches and tools exist to guide conservation decisions (Acosta et al. 2016; Bower et al. 2018; Schwartz et al. 2018). Frequently used frameworks include systematic conservation planning (SCP), adaptive management (AM), structured decision making (SDM), and frequently used stand-alone prioritization concepts include multi-criteria-decision-analysis (MCDA), and cost-effectiveness analysis (CE). These differ in key aspects (Table 3. 1) due to their evolution and use in different contexts. Moreover, the use of any given framework or approach does not ensure that all of the key elements of sound decision-making are incorporated in any given decision (Game et al. 2013; Gregory et al. 2012; Kahneman and Tversky 1984; Wilson et al. 2006; 2007).

Table 3. 1 Frameworks and prioritization concepts that are frequently used to support decisions for conservation management strategies

Framework / Prioritization concept	Key aspects	Key reference
Systematic Conservation Planning	- Spatially explicit planning for protected areas - Map as output - Based on selection of distinct planning units	(Margules and Pressey 2000; Moilanen, Possingham, et al. 2009)
Adaptive Management	- Monitoring information used to adjust repeated decisions - Experimental set up - Learning about effect of management intended	(Keith et al. 2011)
Structured Decision Making	- Importance on clarifying decision problem and eliciting appropriate objectives and metrics - Explicit comparison of alternatives, - Often with transparent quantification of trade-offs	(Gregory et al. 2012)
Multi-Criteria-Decision-Analysis	- Focus on relative importance of different objectives - Scoring, weighting and summation of different criteria and/or objectives to rank options	(Adem Esmail and Geneletti 2018)
Cost-Effectiveness Analysis	Consideration of cost without compromising objectives other than cost: comparison based on return of investment	(Wilson et al. 2009)

Each of the five commonly used options in Table 3.1 utilizes distinct steps in the decision-making stage of planning processes. These steps aim to ensure important elements are included to decrease the risk of not meeting objectives (Nicholson and Possingham 2006). Most frameworks describe steps at a high level, such as defining objectives or developing alternatives. This recognises that each decision context may require a tailored approach or tool to be used in each phase. While vagueness within decision support options provides flexibility to account for context, it can lead to unintended neglect of the key steps.

Based on fundamental decision theory texts in the context of conservation (Gregory et al. 2012), we identify five crucial elements of a robust decision process against which to evaluate published descriptions of conservation focused decision processes: 1.) identify clear objectives, 2.) identify measures of anticipated impacts of planned actions with a clear theory of change, 3.) document financial and social constraints 4.) characterize uncertainties and conduct sensitivity or uncertainty analysis 5.) characterize and measure trade-offs. Evidence of the importance of these five decision elements is discussed in more detail in Supplementary Material S3.1. The five critical elements of decision making that we highlight here have been highlighted as critical in decision-making among wildlife managers (Fuller et al. 2020).

Evaluating decision processes in conservation

Recent studies that identify the factors leading to success and failure of decisions made in conservation management include strong recommendations for evidence-based conservation (Sutherland et al. 2004; 2020), the creation of data repositories (https://www.miradishare.org/ux/home, https://www.conservationevidence.com, https://marinescp.jcu.io), and reviews that provide an overview of conservation management effectiveness (Bayraktarov et al. 2016; Geldmann et al. 2018; McIntosh et al. 2018). Attempts to quantify the effectiveness of implemented conservation plans by measuring outcomes have largely failed to produce definitive findings due to mixed evidence (Edgar et al. 2014), data paucity (McIntosh et al. 2018) and high variability between conservation contexts (Lester et al. 2009). However, the importance of sound decision-making is widely accepted (Butt et al. 2020; Carwardine et al. 2019; Visconti and Joppa 2015; Wilson et al. 2006). The damaging effects of neglecting elements of good decision-making during planning are well documented. Failure to identify meaningful objectives (Bond et al. 2008; Game et al. 2013), missing theory of change as link between actions and threats (Kuempel et al. 2019), failure to include constraints such as costs or feasibility (Symes et al. 2016), or failure to conduct sensitivity analysis to evaluate uncertainty (Larson et al. 2016; Mazor et al. 2014; Runge et al. 2016; Sutton and Armsworth 2014) can lead to suboptimal or counter-productive decisions. A systematic assessment of decision-making for conservation actions can identify the degree to which the key elements of sound decision-making are being utilized in conservation planning and management.

Here we provide a comparative and quantitative review of the extent to which the elements of decision-making are utilized in published work on conservation decisions problems. Our review is based on 466 examples drawn from the peer-reviewed literature and provides insight into the types of conservation decisions that benefit from the application of all elements set out in decision theory. We discuss the elements of decision-making that might need to be bolstered to produce more robust conservation decisions and better outcomes.

Methods:

Data collection

We use a systematic review protocol (Moher et al. 2009) through a keyword search of the Web of Science, targeting literature published between 2009 and 2018. Our goal was to find documents describing decision-making that selects a strategy from a range of options to address a specific environmental problem. A search was conducted in December 2018, using the term "decision-making" and five common decision-aiding frameworks (Bower et al. 2018; Schwartz et al. 2018) and prioritization methods (Supplementary Material S3.2). Our search yielded 7106 publications, which were subsequently screened for a conservation-related decision-context, resulting in 1218 publications that were read in detail. Of these, 466 examples described a decision process of prioritizing management strategies in adequate detail to understand the decision process, and information on five decision elements and four descriptive factors was collected from each (Table 3. 2).

Table 3. 2: Assessed categories that were classified within this literature review

Five elements for robust decision-making	**Classification (presence/absence)**
Objectives	Are environmental objectives quantitatively expressed?
Actions and threats linked in a theory of change	Is there a clear link to a threatening process? Examples were classified based on (Salafsky et al. 2008). As conservation actions aim in most cases to mitigate existing threats that cause a decline or deterioration, we focused on the inclusion of a specific threat as proof of an existing theory of change in the decision-making process.
Socio-economic considerations	Are socio-economic objectives included? Only examples that included a specific objective regarding social or economic factors that were considered in the choice between options were classified as "socio-economic objectives present"
Sensitivity and uncertainty analyses	Are sensitivity or scenario analyses done to test for effects of uncertainty?
Trade-offs	Are trade-offs between different objectives described and explored? Only examples that used trade-offs to make a choice between options were classified as "trade-off present"
Four descriptive factors	**Multiple entries possible**
Decision support option	Five frameworks and prioritization strategies, or "mixed" if more than one was used (Table 1.1)
Context	If collaboration with management authorities or implementation were explicitly described: "conservation practice", if not: "academic"
Type of management	Five types of proposed management actions based on (Salafsky et al. 2008)
Location	Country in which proposed management was located

If a publication described examples of different decisions, each individual decision was recorded as one example (see, for example, Canessa et al. 2016). If case-studies were referred to with citation, they were excluded to avoid redundancy. Horizon Scanning and Strategic Foresight (Cook et al. 2014) had been initially included in the search but were not part of the analysis as no example was found that described a conservation-related decision between available management options.

Table S3.3 provides full information on the coding scheme. All code and data are available on figshare [10.6084/m9.figshare.13777216].

Reliability of data classification

Several measures were taken to improve clarity of categories and to identify errors and variation in the data classification. Extraction of qualitative information from text is not free from bias and errors (Marcoci et al. 2019; Marry L. McHugh 2012). It is common that highly trained experts come to different conclusions when faced with the same evidence (Kahneman et al. 2021). Such unwanted variability in judgments can have a greater impact than bias. This variability is to be expected when classifying text and can be explored by quantifying variability across multiple raters. We assessed the reliability of the extracted data using 25 examples (Supplementary Material S3.4). Percent agreement between four additional raters and the lead author was well above conventional thresholds of 75% for inter-rater-reliability-testing for all categories. The error rate of the main rater was lower than the additional raters.

Results:

A profile of conservation decisions

Our quantitative analysis included 466 examples (Table S3.5, S3.9). About a third of the 466 examples described either a collaboration with authorities that were interested in finding a solution to a particular conservation problem or partial or full implementation at the time of publishing (128 examples, referred to as “conservation practice” in the following). Two thirds (338 examples) have been conducted without any indication that decisions were implemented by a practitioner, manager, or agency (referred to as “academic” in the following). The numbers of examples for different decision support approaches were biased towards systematic conservation planning (212) and adaptive management (106), while all other, as well as mixed approaches, contributed 29 - 47 examples each (Figure 3. 2, Table S3.4).

We found a clear difference in how often the five key decision elements were used overall and in combination. The description of only one of the elements was rare in both academic and conservation practice contexts. In academic contexts, the combination of three or four elements was more than twice as likely as the combination of two or five elements. In conservation practice contexts, numbers of examples that combined two, three, four, or five elements were similar (Figure 3. 1). In total, less than half of all examples (211 examples: 52% of conservation practice and 37% of academic examples) used more than three of the important decision elements in combination. The relative frequency of examples with five elements was slightly higher in conservation practice contexts. When three elements were combined, trade-off, link to threat through a theory of change and socio-economic constraints were more often missing than quantitative objectives or sensitivity analysis. When four elements were combined, 95 examples excluded trade-offs and 21 linking to a threat through a theory of change, while the other elements were less often missing. Only 27% of all examples explicitly documented deliberation on trade-offs. Each of the other elements was described in 70-84% of examples.

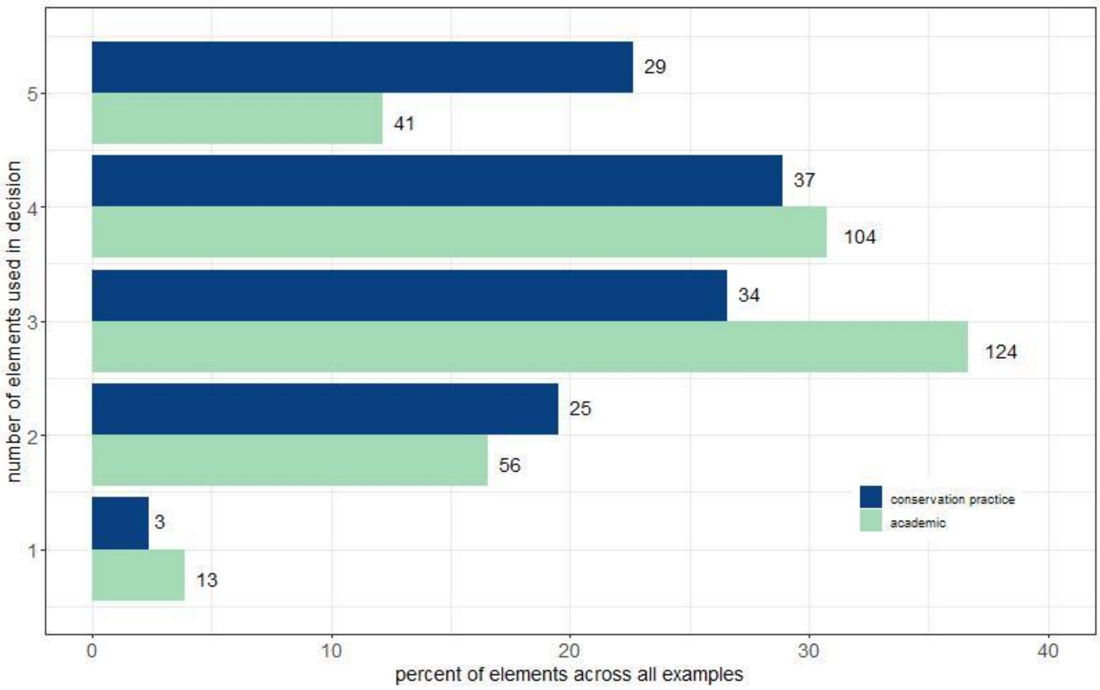


Figure 3. 1: Number and proportion of key decision elements that are described in academic and conservation practice contexts.

We found clear differences when comparing how often specific decision support options were used in academic or conservation practice contexts and how often each used the five different elements (Figure 3. 1,Figure 3. 2). Adaptive management was the most often used decision support approach in conservation practice contexts and the second most often used in academic contexts (Figure 3. 2). Only a few of these examples used all five decision elements in combination, and a large fraction used only two or three elements. Quantitative objective and socio-economic objectives were not described in approximately half of the academic and conservation practice examples.

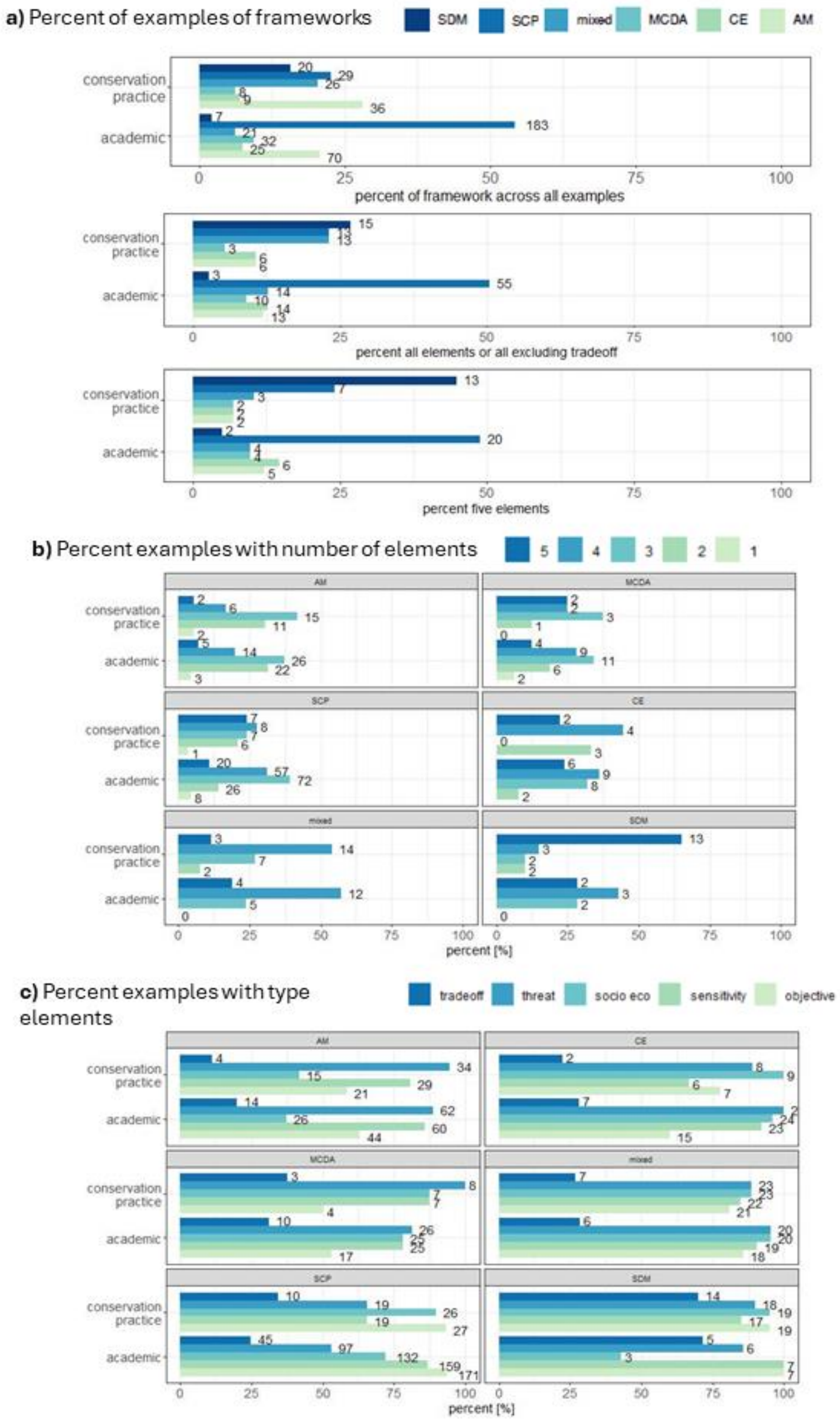


Figure 3. 2: Figure 2a: The use of frameworks in conservation practice and academic contexts in general (top row) and in examples that use all elements (bottom row). The middle row shows the examples that use either all elements or exclude only trade-offs. The x-axis shows percent within each group of academic and conservation practice examples. Each bar is labeled with the number of examples.

Figure 2b: The use of elements within each framework in conservation practice and academic contexts. The x-axis shows percent within each framework of academic and conservation practice examples. Each bar is labeled with the number of examples.

Figure 2c: The use of specific elements within each framework in conservation practice and academic contexts. The x-axis shows percent within each framework of academic and conservation practice examples. Each bar is labeled with the number of examples.

Systematic conservation planning comprised the largest fraction of examples in academic studies (Figure 3. 2a). Half of these examples did not describe a clear link to a threat through a theory of change, and a third did not include any socio-economic objectives (Figure 3. 2c). There were far fewer examples of SCP in conservation practice contexts, and in those examples, a relatively low proportion clearly described a theory of change that links management to a threat and conducted sensitivity analysis. In contrast, a higher proportion of applications considered documented socio-economic objectives (Table 3.2). A higher fraction of SCP examples used five elements in conservation practice contexts than in academic contexts. At the same time, almost a quarter of the conservation practice examples for this framework used only one or two elements (Figure 3. 2b).

Structured decision making was the only framework that was used predominantly in a conservation practice setting (74%), while over 60% of examples of each of the other decision support strategies were set in an academic context (Figure 3. 2a). Conservation practice examples of SDM had high inclusion rates for all elements. Academic examples of SDM included socio-economic objectives less often (Figure 3. 2c).

Compared to other decision support options, examples of multi-criteria decision analysis rarely articulated a quantitative objective in both conservation practice and academic contexts. About a third of academic examples that used cost-effectiveness analysis did not describe quantitative objectives for the biodiversity value that was supposed to benefit from the management, and a third of conservation practice examples that used cost-effectiveness analysis did not describe any sensitivity analysis or other exploration of uncertainty.

Structured decision making described all five elements in 28% of examples, compared to 24% of cost-effectiveness analysis examples, 19% examples with mixed decision support, 15% of systematic conservation planning examples, 12% of multi-criteria-decision-analysis examples and 7% of adaptive management examples (Figure 3. 2a). To account for the rare use of trade-offs, we tested a relaxed condition for including them, with similar results (Figure 3. 2a). There was no visible temporal trend for the frequency of using four or five elements in any of the frameworks (Supplementary Material S3.6).

Application of all elements of decision-making within different types of conservation problems

Particular frameworks were preferred for specific types of conservation problems. Several patterns emerged in the analysis of how often more than three elements were included in each type of management in conservation practice and academic contexts (Figure 3. 3).

Decisions were made most often within pre-selected management strategies (see different panels in Figure 3. 3). Only about a quarter of all examples (95 out of 466) considered more than one management strategy in the decision-making process ("mixed" box in Figure 3. 3a). The majority of examples considered options for one pre-determined strategy exclusively (202 spatial prioritization (including protected area planning), 70 threat abatement, 42 restoration, and 27 population management). The most common mixed combinations were spatial prioritization and restoration (26 examples), threat abatement and population management (14 examples) and threat abatement and restoration (13 examples). Seventeen examples did not match the five management categories.

Some frameworks were found more often for a specific type of management than other frameworks (differences of height of bubbles in each panel): While examples for mixed management can be found for all frameworks, spatial prioritization was most often conducted with systematic conservation planning, and most decisions on restoration were made within an adaptive management framework.

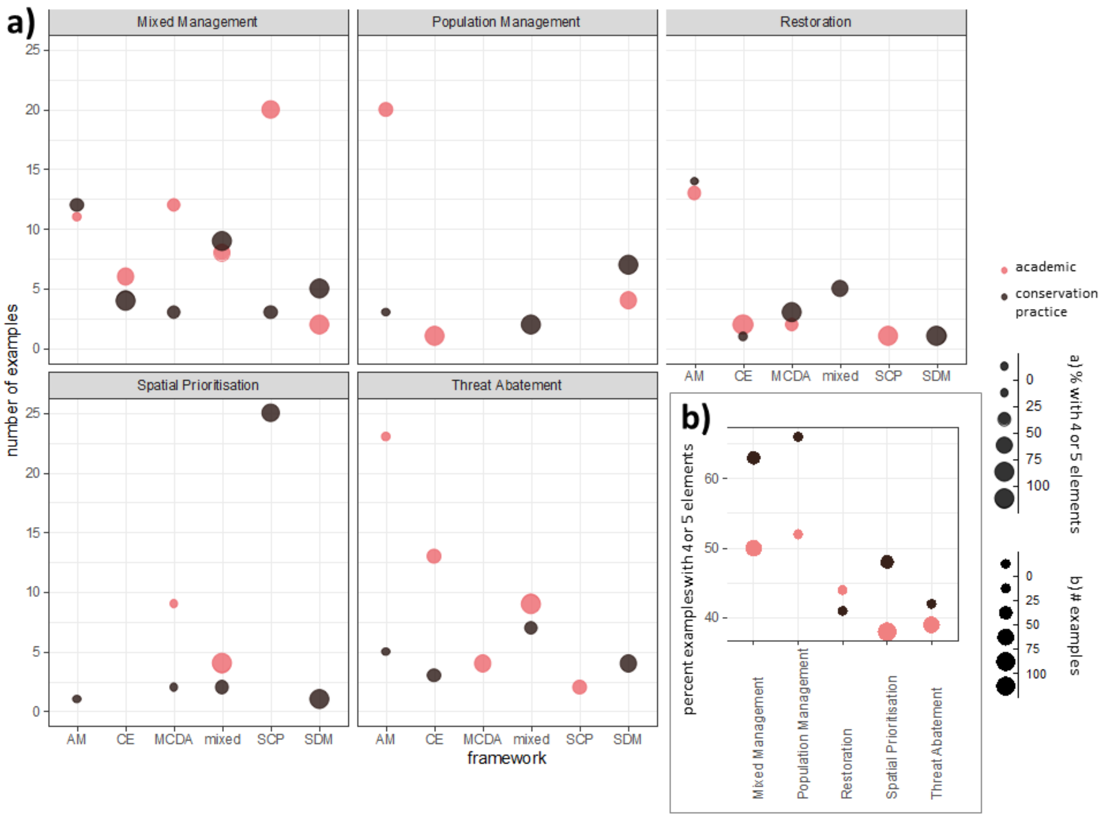


Figure 3. 3: Panel a): Bubble plot of how often different frameworks were used in academic and conservation practice examples for different types of management. The y-axis shows the number of examples, while the size of the points represents the fraction [%] that used four or five elements. Note: in order to visualize differences in the numbers along the y-axis, the high number of examples that use systematic conservation planning for spatial prioritization is only shown in panel b). Panel b): The frequency of using all five elements within different management types ranges from 38% -66%, with spatial prioritization and threat abatement in academic contexts at the lower end and population management and mixed management in conservation practice context at the higher end.

Some frameworks were utilized differently in academic and conservation practice contexts (see difference in height for each color): Mixed management examples in academic contexts used most often multi-criteria-decision-analysis and systematic conservation planning, but mixed management examples in conservation practice contexts used all other frameworks more often. Examples for population management and threat abatement in academic contexts used most often adaptive management, while the same type of management in conservation practice contexts used frequently other frameworks.

Some types of management were particularly prone to decision-making with a low number of decision elements (smaller points that are higher up along the y-axis in each panel and lower points in Figure 3. 3b). For example, restoration and mixed management examples used adaptive management often in both conservation practice and academic contexts, but these examples included four or five elements at a lower rate than multi- criteria-decision-analysis or mixed approaches. Academic population management examples used most often adaptive management, with a lower frequency of using 4 or 5 criteria than among the fewer examples of cost-effectiveness analysis or structured decision making. Population management examples used mixed frameworks or structured decision making as often in conservation practice contexts as adaptive management and included four or five elements more frequently. Panel b in Figure 3. 3 shows that decision-making for threat abatement and restoration was more prone to omit two or more elements both in academic and conservation practice contexts, and spatial prioritization in academic examples used least often more than three of the key elements.

To be sure the likelihood of including all elements was influenced by specific decision support options and not driven by specific authors, particularly for decision support options with fewer examples, a co-author network was created for all examples that used five elements. The network (Figure S2. 3) shows a high diversity of authors in general for all decision support options, with one large network of authors of academic examples who are connected through the Centre of Excellence for Environmental Decisions in Australia.

Geographic distribution of examples and use of decision elements

Although examples of conservation decisions existed for over 80 countries across all continents, the location of the examples was biased towards the USA and Australia. The two countries provided more than a third of all examples overall, as well as for academic and conservation practice contexts individually (Figure S2. 4). Academic examples were found for 52 countries and conservation practice examples for 33 countries. However, there were only six countries with more than 2 conservation practice examples, and no conservation practice examples were found for most African, Middle Eastern and Latin American countries.

Discussion

We have shown that robust conservation decisions according to standards of decision science exist across all decision support options in academic and applied contexts. But the bulk of academic and applied studies that document decisions that we evaluated in this study do not apply all of the key elements of decision science, or at least did not report them. We found differences in the use of decision elements between decision support tools in academic and applied contexts and across different management activities. Our results imply that problems that stem from omitting specific key elements, including risking further species' declines when the planning lacks quantitative and ecological meaningful objectives (Carwardine et al. 2009; Game et al. 2013; Pfab et al. 2011), implementing actions that do not address the key threats (Bayraktarov et al. 2016; Devillers et al. 2015) or creating socio-economic problems when not acknowledging the human context during the planning (Bode et al. 2010; Wittemyer et al. 2008), are likely to be common across the conservation discipline.

Of the decision support frameworks we considered, structured decision making is the most recently developed framework, and therefore draws on the most complete suite of insights from decision science. Although applications of SDM most often included many elements, they were also the most underrepresented in our database and almost exclusively from the USA. We believe our results provide great insights into the potential shortcomings affecting decision-making and highlight opportunities for more transparent reporting of important decision elements in publications.

The type of decision support that was used during decision-making contributed more to the differences in the uptake of key elements than whether the activity was academic or applied. There were clear signs that some conservation management strategies are most likely to be at risk of failing to achieve ecologically meaningful benefits due to a propensity to omit key elements of the decision-making process.

Consequences of limited consideration of decision elements in protected area planning

It has been shown over ten years ago that the locations of protected areas are biased towards places that do not face a threat of land conversion (Joppa and Pfaff 2009), and many publications have discussed the shortcomings of protected areas as a tool to protect biodiversity (Barnes et al. 2018; Cooke et al. 2023; Mora and Sale 2011; Naumann et al. 2021; Pressey et al. 2017). These discussions focus particularly on threatening processes, and if and how they are included in the planning. Our results show that it is still not common practice to include a clear description of key threats and the expected mechanism of mitigation in publications of systematic conservation planning. Similar evidence has been published in an EU context (Hermoso et al. 2022).

If our results are representative of SCP in the real world, many of the protected areas could have limited potential to protect biodiversity from existing threats if they were implemented because lower opportunity costs cause a bias towards prioritizing areas with low or no threat pressure. The rezoning of the Great Barrier Reef is a famous example of this particular problem in protected area planning. Shortly after the plans had been made public, critical voices highlighted the limited benefits in terms of protection from threats to biodiversity, due to the spatial exclusion of commercial fishing areas (Devillers et al. 2015). While planning without a clear conceptual link between the intensity of threats in spatial planning units minimises opportunity costs and facilitates implementation by reducing conflicts with resource users, protected areas become biased towards locations that are exposed to limited or no threats.

The low rate of socio-economic objectives in academic studies could be explained by the focus on specific aspects with the aim to show novel approaches in systematic conservation planning. However, the frequent lack of any sensitivity or scenario analysis in a third of applied examples indicates that addressing uncertainty is not widely considered when making decisions for a protected area. This may lead to conservation area designs that are susceptible to failure of key assumptions about, for example, the location of key species habitats, or how species may respond to changing climates (Moilanen et al. 2006).

Consequences of limited use of the full potential of adaptive management for threat abatement and restoration

The lack of quantitative objectives and socio-economic objectives has been stated as one of the most common mistakes in conservation decision-making (Game et al. 2013). The fact that these key decision elements are often missing in documentation of adaptive management might have broader implications for many restoration and threat abatement projects, as the clear majority of examples that we found for these management strategies used adaptive management for decision support. If adaptive management is primarily used to monitor changes in real-time and practices "learning by doing", often without clear ecological objectives (Carwardine et al. 2009), it is questionable if these projects have the capacity to deliver the intended conservation outcomes (R. Gregory et al. 2006; Riley and Gregory 2012). An example from our survey is Briceno et al. who compare interventions against poaching for yellow shouldered parrots but do not provide any quantitative objective regarding the level that poaching needs to be reduced to keep the population at viable levels (Briceño-Linares et al. 2011). The lack of quantitative objectives was also common in decisions based on cost-effectiveness analysis, where often only threats were targeted, without a clear measure of how a reduction of a threat would benefit a species or habitat. Examples included improving water quality to benefit waterfowl with no quantitative objective for the waterfowl (Martin-Ortega et al. 2015), sediment reduction for the Great Barrier Reef without any quantitative objective for reef related biodiversity (Bouma et al. 2011), or control of an invasive species without a quantitative objective for biodiversity that would benefit from the control (F. A. Johnson et al. 2017). The plain fact that cost-effectiveness analysis is a means to find the best ratio between costs and benefits might explain why targets were often not articulated in more detail, but it highlights how easily important elements of the decision process can get overlooked.

Developing effective adaptive management plans is challenging, resulting in few success stories (R. Gregory et al. 2006; Riley and Gregory 2012). Similar to our findings, a recent review of adaptive management found few applied AM projects compared to academic studies (Westgate et al. 2013). The review also suggested that often decisions makers used the 'adaptive management' label when the actual approach did not meet the standards of the theory behind it. This may also explain the low number of described elements in our results (Figure 3. 2 and Figure 3. 3).

Restoration attempts reportedly have a low success rate and often neglect socio-economic criteria or considerations of threats in a theory of change (Bayraktarov et al. 2016; Suding 2011; Wortley et al. 2013). Restoration is a key conservation activity worldwide and is fundamental to achieving global biodiversity framework goals (The Kunming-Montreal Global Biodiversity Framework 2022; Fischer et al. 2021; Strassburg et al. 2020). A greater emphasis on a rigorous decision process, particularly under adaptive management, seems to be a promising pathway to improve success rates.

Different preferences of decision support options in applied versus academic examples

Systematic conservation planning and adaptive management are not necessarily the most common decision-aiding support options in the conservation practice, despite their popularity within academic case studies. The dominance of these decision support options in academic contexts might obfuscate important other questions and problems that applied conservation managers are interested in. The misalignment might be partly caused by the ease with which some tools can be used to work on well-established and intellectually interesting problems, like the use of Marxan for the minimum-area / maximum-coverage in spatial planning, or the use of Bayesian-Belief-Systems and Value-of-Information in adaptive management. The high proportion of structured decision making in conservation practice might be an indication of the usefulness of processes that are more closely linked to decision science in applied contexts.

Spatial patterns in decision approaches

Examples in which all five critical elements of decision making were applied were strongly biased towards Australia and the USA. Recent literature reviews on biodiversity confirm the persisting bias in publications towards very few countries, which do not match with the distribution of biodiversity (Di Marco et al. 2017; Wilson et al. 2016). Data gaps in meta-analyses are likely not stemming from a lack of research, but rather from language barriers that prevent existing literature from being visible in major English online repositories (Amano et al. 2021; 2023; Hannah et al. 2024; Konno et al. 2020).

Efforts such as summaries for particular management types are an effective way to make existing efforts visible (Bayraktarov et al. 2020) but are needed on a much larger scale. In the current state, the literature on decision processes for conservation management seems to paint a very limited picture of conservation management decisions around the world.

Reasons for limited uptake

Conservation science is not limited to realistic planning but also aims to progress methods and theoretical concepts or reports new data. Therefore, a certain amount of literature on decision processes, particularly in academic contexts, is expected to focus on the nuances of specific novel aspects of a complex decision instead of reporting in detail on the whole process. However, we also found a large fraction of applied examples with low numbers of critical decision elements. This indicates that insights from decision-science have not yet become standard in decisions that inform conservation practice, or at least are not reported in the published documents that describe practices. There is a range of potential scenarios in which the use of all elements may not be necessary or possible. For example, we could not assess if conservation scientists used key elements but did not adequately describe the details or simply failed to present them. One reason for not using some elements is the inherent trade-off between resources spent at planning, including decision-making, and resources spent on action (Buxton et al. 2020). In many cases, conservation actions are opportunistic (Meir et al. 2004; Pressey and Bottrill 2008), and decisions have to be made quickly, or budget and expertise do not allow for a detailed decision-making phase. For example, the deliberation on trade-offs between multiple objectives can easily become complex and time-consuming. Involving stakeholders to scope out additional objectives and discuss trade-offs requires time, resources, and additional skills of facilitation and maneuvering group dynamics, which adds to the complexity of a more narrowly framed problem context. Scoping and running additional ensembles and sensitivity analyses is similarly time and resource consuming. Although these reasons are compelling arguments for the necessary balance between feasibility and rigor, we believe it is most important to acknowledge the importance of key elements during decision-making and to be transparent on the reasons when omitting them. That way, the conservation community would facilitate understanding and best practice, and make it easier to evaluate successes and failures.

Representativeness of results

It could be questioned if the 466 examples that we identified in this review are representative of the comprehensive literature on academic and applied decisions on conservation management actions. There are likely many published examples of decision processes that do not include the phrase "decision-making" in the main text, and only a small fraction of existing gray literature is synthesized into peer-reviewed publications. However, the identification of 128 conservation practice examples in a sample drawn from a database of peer-reviewed literature was much higher than we expected when considering the often cited and controversially discussed "implementation gap" (Sunderland et al. 2009). Additionally, the use of key decision support elements was more strongly related to the use of specific frameworks than to the context of applied conservation practice versus academia. Hence, we believe our sample to be representative of the broad range of contexts, including genuine applications.

The number of identified publications that utilize multi-criteria-decision-analysis is similar to a recent review (Adem Esmail and Geneletti 2018). In contrast to Esmail et al., we did not find a strong dominance of locations in Europe, with similar numbers of examples in the USA. This difference might stem from our focus on management actions for biodiversity conservation, which excluded a larger number of site-selection studies for industrial purposes. Another difference is the higher rate of sensitivity or uncertainty analysis, with 80% of examples in our review including some sort of sensitivity or uncertainty analysis, while Esmail et al. reported rates under 60%. A dominance of academic examples for systematic conservation planning is supported by earlier assessments (Knight et al. 2008; Kullberg and Moilanen 2014), but also contrasted by a recent survey that found similar numbers of examples, but where most were intended for implementation (Sinclair et al. 2018). Overall, we felt that the total numbers of papers and different frameworks can, compared to these other studies, be considered as a representative sample.

Classifying text is not a trivial task, as a different judgment on the same issues is common among experts (Kahneman et al. 2021). Even though we developed and tested instructions for choosing categories during the coding phase, making a judgment on the use of a specific element based on descriptive text is difficult. For example, one publication (Koehn and Todd 2012) focused on the importance of trade-offs, and described it with theoretical examples, but did not use it for a final decision. A second paper (Chadés et al. 2015) mentioned trade-offs only briefly, but presented a figure that showed that they based their choice of action on information from a trade-off analysis in the form of a cost-benefit curve. To avoid difficult subjective judgments, such as coding the inclusion of trade-offs based on the judgment if it has been described in "enough" detail, we decided to code a trade-off only as present when it was clearly used to inform the final choice of management strategy. This is a clearer condition, as it did not need subjective judgment on how much description is enough and where to draw the line when trade-offs were described (sometimes in great detail) but were not used. We acknowledge that we were only able to classify what was described in the text. In many cases, key elements might have played a role in the decision but were not described in the publication and could therefore not be coded. Published documents about decisions that do not describe all key elements that were used are unfortunately not very useful to inform readers on how the decision was made and how rigorous the process was, despite the text's potential usefulness for other matters. Our results suggest that it is common practice among conservation scientists and practitioners to omit key decision elements frequently in their decision-making processes, or to at least not include them in descriptions of these processes. If this is true, the scientific literature is not a good place to look for fundamental guidance for decision-making processes but can only provide additional inspiration when it comes to novel approaches or specific details in the decision process.

Conclusion

If conservation scientists and practitioners want their publications to improve and inform management strategies, decision processes should be based on insights from decision-science, and the use of key decision elements should be reported more transparently and comprehensively. The intent of our study is to encourage the conservation community to embrace the discussion and use of these five elements of robust decision-making, and to report transparently about factors that hinder their inclusion in decision-processes. Academic studies need to increase the focus on decision-making strategies and management types that are common in applied contexts. Some specific circumstances do not allow the inclusion of all elements due to lack of data, time constraints or other means, but decision-makers need to be aware of the increased risks that they invite through a less rigorous decision-making process. While outcomes of conservation actions are most often uncertain due to the inherent complexity of natural systems and their inherent uncertainties, the process of decision-making can be used to judge the quality of the decisions being made (Hammond et al. 1998; Riley and Gregory 2012). Such a process leads to the creation of feasible and realistic strategies for the implementation of management actions on the ground. Time and budgets are limiting existing efforts to protect our fast-disappearing natural heritage on this planet. Robust decision processes should be a high priority when people make choices about the course of action that is most promising to change the ongoing trend of loss of biodiversity. Finally, in order to understand and learn from the current state and trajectory of applied conservation management on a global level, there is a need to translate existing descriptions of conservation decisions from other languages into the English-speaking literature. We recommend that decision-makers seek detailed instructions beyond publications in the field of conservation to be able to employ rigorous practice during the decision-making process when planning for the conservation of biodiversity.

Chapter 4

Group discussions improve reliability and validity of rated categories based on qualitative data from systematic review

Abstract

The number of literature reviews in the fields of ecology and conservation has increased dramatically in recent years. Scientists conduct systematic and other literature reviews with the aim of drawing conclusions based on the content of a representative sample of publications. This requires subjective judgments on qualitative content, including interpretations and deductions. However, subjective judgments can differ substantially even between highly trained experts that are faced with the same evidence. Because classification of content into codes by one individual rater is prone to subjectivity and error, general guidelines recommend checking the produced data for consistency and reliability. Metrics on agreement between multiple people exist to assess the rate of agreement (consistency). These metrics do not account for mistakes or allow for their correction, while group discussions about codes that have been derived from classification of qualitative data have shown to improve reliability and accuracy. Here we describe a pragmatic approach to reliability testing that gives insights into the error rate of multiple raters. Five independent raters rated and discussed categories for 23 variables within 21 peer-reviewed publications on conservation management plans. Mistakes, including overlooking information in the text, were the most common source of disagreement, followed by differences in interpretation and ambiguity around categories. Discussions could resolve most differences in ratings. We recommend our approach as a significant improvement on current review and synthesis approaches that lack assessment of misclassification.

Introduction

The number of reviews in the fields of ecology and conservation has increased dramatically in recent years. Reviews take science to a meta-level that is needed to transcend the focus and unique circumstances of individual studies, enabling generality. When researchers conduct a review, they search the published literature with a specific question in mind, and often use a rubric, or filter, to find publications that contain relevant content for the question they want to answer. General guidelines for conducting reviews and other meta-analysis aim to facilitate unbiased and repeatable results and include recommendations for asking a second and sometimes subsequent researcher(s) to go through the same process of selecting or interpreting texts using a subsample of included publications and compare the judgments that were being made (Côté et al. 2013).

A standard part of the methodology when conducting a review is to extract data from the existing literature. While systematic reviews often classify content into categories, which is most often done by judging content based on a coding scheme, narrative reviews make judgments on content in a rather informal way, possibly drawing more on subjective intuition or interpretation without a standardized protocol. Unfortunately, making judgments about content is not a trivial task, and misclassification can easily occur (Wallace and Jago 2017; Failing and Gregory 2003). If error or bias are not detected during peer review, the impact on the field of science could be substantial and long lasting, as even retracted studies continue to collect citations (Bar-Ilan and Halevi 2017; 2018). The citation report from Reuters Web of Science for systematic or literature reviews in the field of ecology and conservation shows a steady increase of reviews with an average citation rate of 76 and an h-index of 326 as of June 2021, restricted to reviews and journals with focus on biology and ecology and based on the search terms “systematic review” OR “literature review” AND “ecology” OR “conservation”. As reviews are rarely replicated and are on average more than twice as often cited as other publications, it is important to ensure the reliability and validity of the coding categories used. Unfortunately, this is not common practice: for example, only three in the 26 most cited and none of the 24 most recent publications that we found in our Web of Science search report either having conducted any reliability checks or state the general importance of doing so.

Content analysis differentiates between three types of content that differ in the amount of interpretation a reader must do. These types are manifest (coding based on pure detection), latent pattern (coding based on detection plus additional cues) and projective content (coding requires deduction) (Potter and Levine-Donnerstein 1999). Classification that goes beyond manifest content, brings subjective judgments into the process and hence uncertainty. Processes that include subjective judgement in addition to pure detection require validation and need to be reliable because of the risk of errors being made during interpretation of different cues in the text. When additional cognitive tasks beyond detection of word are involved in a classification task, for example interpreting the context a word is used in and making a judgment based on this interpretation if a specific condition is met, additional possible sources of mistakes or misinterpretation are introduced. General recommendations for reliability tests suggest the use of multiple raters in the process of coding in order to produce reliable data (Campbell et al. 2013; Marcoci et al. 2019; O'Connor and Joffe 2020). Information on agreement is commonly used during a testing phase to identify problems like unclear categories in the coding scheme, and, based on parallel coding of a smaller subset, as an indicator for the reliability of the whole data set.

Multiple metrics (Krippendorff 2004; Hayes and Krippendorff 2007) have been developed to assess rate of agreement between raters as a proxy for reliability. Although reliability is a prerequisite for validity, reliability metrics cannot inform about the validity of tested data (Krippendorff 2004). There is a difference between how often people produce the same code (reliability) and how often raters give the best possible answer compared to the actual content of the source (validity). Therefore, agreement that is based on misclassification can increase reliability but at the same time decrease validity, and in the worst case will make people trust data that does not reflect the actual content of the coded texts.

Unfortunately, testing for validity is difficult. While an objective standard exists for manifest content, against which any rating can be compared against (for example presence/absence like counting the frequency of a word, or testing for a substance in a blood sample), an objective standard in form of an uncontroversial agreement on interpretation does not exist for latent pattern or projective content and needs to be constructed (for example the use of a word in a specific context, or the contribution of a detected substance to a health problem). The construction of any standard for latent pattern and projective content requires a certain amount of human judgment, which is inherently subjective, and the resulting standard can therefore never be fully objective. The practice to designate the main rater as a point of reference is common (Garrison et al. 2006), but has been questioned because assumed expertise has been often shown to be unjustified when tested (Burgman et al. 2006). A thorough, rigorous process for accounting for subjectivity and error is therefore needed.

The situation that an objectively perceived correct interpretation is unknown and all that can be used is a well-informed subjective judgment is very similar to the context of expert judgment (Hanea et al. 2017; Rowe and Wright 2001) and expert elicitation (Martin et al. 2012). Therefore, measures that are used to improve data quality in these areas of research, particularly the use of group discussions, seem to be promising tools for testing the validity of coded data in content analysis.

The positive impact of group discussion on agreement between independent raters has been described in the field of medicine (Levine et al. 1998). More recent research on expert judgment and elicitation has shown that the reliability and accuracy of judgments usually benefits from on exchange of thoughts and assumptions of individual raters in a group setting (Burgman et al. 2011; McBride et al. 2012; Mcbride and Burgman 2012; Shea et al. 2020; Hanea et al. 2017; Hemming et al. 2018). Even though many of these examples focus on estimation of quantitative data in natural sciences and risk analysis, similar recommendations can be also found in the social sciences regarding qualitative data (Garrison et al. 2006), specifically the importance of discussion during rating exercises when there is *"great sensitivity not only to obvious meanings but also more subtle meanings, and where coders have different levels of knowledge in this regard"* (Campbell et al. 2013). In the context of business decisions, discussions have been identified as more important than rigorous process (Garbuio et al. 2015). In addition to biases, which represents directional errors, errors that appear as unwanted variability in judgment of people who must choose between options has been termed ‘noise’, and is often surprisingly high across many professions despite extensive education and training (Kahneman et al. 2021). Here we consider *mistakes* as errors that create noise and use the term *error rate* when referring to the frequency of these mistakes.

Reading scientific publications is intellectually demanding because their comprehension requires knowledge of the used terminology and concepts in the context of the relevant discipline. Knowledge held by individuals will be similar across scientists from a particular field, but will differ in breadth, depth, nuances, and school of thought. In addition to the differences in expertise and the ever-present chance of making simple mistakes, scientists are subject to different kinds of biases when making judgments, both on their own, and when in groups. Protocols have been developed that enable people to make judgments with as little bias as possible (McBride et al. 2012). To capture the widest possible range of knowledge and subjective judgment, it is important to give individuals the chance to make initial judgments on content on their own. Independent judgments protect from biases introduced through human interaction, such as groupthink and dominance. However, to mitigate biases that matter in individual thought processes, such as availability bias or confirmation bias, feedback and discussion of assumptions and evidence is required.

By facilitating a group discussion after each rater has completed a coding task individually, individual and group relevant biases can be addressed, while unintended disagreement can be corrected when the raters themselves believe they made a mistake and only true disagreement based on convictions are retained. Where misclassification has occurred due to simple mistakes, it is likely that raters, if given the chance to correct their mistakes, will be able to resolve some disagreements, while new disagreements might be discovered. At the same time insights into the error rate of individual raters can be gained by quantifying how often raters change their coding decisions, for each category within all rated texts, after discussion. The resulting data would likely be more reliable and more accurate than without such an assessment of evidence for produced codes.

Building on insights from expert judgment as well as social sciences, we describe a case study that trials a combined assessment of reliability and validity of coded data in three steps: By linking conventional parallel coding (step 1) to a subsequent reflection on their ratings (step 2), followed by a group discussion (step 3), we are able to measure the rate of change due to errors, or changed believes. The analysis of these rates of change in agreement produces metrics that go beyond raw initial agreement rates. These metrics include the percent agreement on categories before and after group discussions and error rates for individual raters and variables. The results allow insights into both reliability and validity of the produced codes.

We demonstrate the application of this protocol using 25 published papers that report on conservation decision processes, coded for a search-term based literature review on conservation decisions (chapter 2 and 3 in this thesis). We demonstrate rater learning by comparing error rates and rates of persistent disagreement using five raters who engaged in individual reading/coding followed by group discussions over a 12-month period.

Methods

Workflow

The 25 examples were randomly selected from a pool of 466 options, while being stratified across subgroups based on citation rate to include examples with highly cited and rarely cited examples in the experiment. Five raters coded in parallel categories for 23 variables (Table 4. 1) using the provided coding scheme (Supplementary material S3.3) and participated afterwards in a group discussion with the option to revise their codes following conversation. Five examples were used in a pilot study to familiarize raters with the task and to test the clarity of categories within the coding scheme, which resulted in adjustments to the coding scheme where raters reported difficulties (Supplementary material S4.1).

The rest of the experiment consisted parallel coding of categories for 23 variables for each of 21 examples (one example overlapped with the pilot) by the same four additional raters during six rounds of coding, followed by a group discussion. The first round included one example; all other rounds included 3-5 examples. Before the group discussion, the individual ratings were compared, and a list of disagreements was sent out to raters to assist with their preparation for the discussion, with a first option to correct for obvious misclassification. This measure was introduced because the first discussion took more than three hours for one case-study, and this change allowed us to successfully reduce the discussion time to one hour per case study, as revisiting the text and confirming evidence for codes was the largest time sink.

The discussions focused on disagreements on any classification. For each category with different classifications from different raters (for example, classification "invasive species" and "pollution" in variables "threat"), each rater shared their evidence from the text on which their judgment was based, as well as any related assumptions. The raters shared their codes for each category in each paper by reading out aloud to create an overview of the range of entries, confirm agreement and discuss existing disagreements. Raters had a second option to adjust their codes during the discussion. The disagreements that remained after code revision opportunities were regarded as true disagreements. Three raters were in the mid or end phase of their bachelor's degree, and one rater was in in the final stages of his Master's degree. Available funds were used as a primary stopping rule and all raters were paid for individual coding and discussions with a standard hourly rate until the money was used up. The moderate sample size of 25 papers is justified as a reasonable sample in light of budget and time constraints (Simmons et al. 2011).

Group effects like dominance and group think were counteracted by having a first round of individual rating to collect the full range of individual codes and reminding raters during the ensuing group discussion that agreement was not a necessary outcome. The distinction between unintentional misclassification and genuine disagreements over interpretation was repeatedly explained, and counterarguments and true disagreement were encouraged. The discussion was facilitated to make sure everyone was heard, and three different types of questions were asked:

1) Can you provide evidence from the text to justify your code?
2) Do arguments for different interpretations of text exist?
    a. Is the coding consistent with instructions?
    b. Is the coding consistent with other coding entries (e.g. ticking the box for the presence of socio-economic objectives might mismatch with empty related fields)?
3) Have we already discussed similar codes and is our argumentation consistent?

Table 4. 1: The 23 variables and the number of possible category codes within them. Combinations of options were coded by entering multiple codes separated with a comma.

	Variable	**Label**	**Type**	**Possible categories (in addition to NA)**
1	Context of decision	implementation	nominal	2 options
2	Framework used	framework	nominal	6 options
3	Country	country	nominal	186 options
4	Continent	continent	nominal	5 options
5	Spatial scale	spatial scale	ordinal	6 options
6	Type of management	management	nominal	5 options
7	Threat type	threat	nominal	11 options
8	Threat presence	threat present	nominal	Checkbox (presence/absence)
9	Species	species system	nominal	14 options
10	Realm	realm	nominal	3 options
11	Type socio-economic considerations	socioeconomic	nominal	7 options
12	Inclusion of socio-economic considerations	Socioeconomic present	nominal	Checkbox (presence/absence)
13,14,15,16	Type environmental, social, economic and other objectives	environmental obj social obj economic obj other obj	nominal	Each 2 options
17	Count objectives	count objectives	numerical	4 options
18	Count of options for decision	count actions	numerical	4 options
19	Trade-off included	tradeoff	nominal	Checkbox (presence/absence)

20	Sensitivity analysis presence	sensitivity present	nominal	Checkbox (presence/absence)
21	Sensitivity analysis type	sensitivity	nominal	9 options
22	Cost included	cost	nominal	4 options
23	Feasibility included	feasibility	nominal	2 options

All data were edited during discussions in Microsoft Excel. One csv file with all codes before each discussion session and one csv file with adjusted codes after the session was created for processing and analysis in R (R Core Team 2020), specifically packages *tidyverse* (Wickham et al. 2019), *reshape* (Wickham 2007), *stringr* (Wickham 2019) and *stringi* (Gagolewski 2020). Data and code are publicly available on figshare [https://doi.org/10.6084/m9.figshare.26889553.v1].

Studies in which the outcome is a quantitative measure often summarize agreement with *kappa*, which is a percent agreement measure which accounts for agreement by random chance, for example when raters have to decide between two categories that are placed next to each other on a quantitative scale. However, our data does not contain many numerical or ordinal variables, hence random agreement was not likely to occur. In addition, metrics like Cohen's kappa, Fleiss's kappa, Krippendorph's alpha or Scotts' pi all make the assumption that coding decisions by raters are made independently (Krippendorff 2004; Hayes and Krippendorff 2007). Our use of a group discussion in the process would violate this assumption. Because of this, and because our data are predominantly nominal and similar to student assessments (O'Donovan et al. 2004), we decided to tailor our analysis to the data, and use percent agreement to calculate metrics of reliability and validity.

We produced two different types of information: first, percent agreement as a measure for reliability of the coding as a procedure that is subject to individual judgment, and second, the frequency with which raters changed their mind about their initial entries as a measure of how trustworthy the code from individual raters were compared to the other raters, and how trustworthy the codes for individual variables were compared to the other variables. This method aims at reducing disagreement based on error, while retaining true disagreements based on interpretation of the categories or the text itself.

Following McHugh (2012), the average percent agreement between the main rater and other raters was calculated as a measure of reliability, and a proxy for the consistency of codes across raters. The average agreement was calculated by first calculating percent agreement for each variable across all coded texts before and after group discussion in pairs between the main rater and each of the other raters, which resulted in four values of percent agreement. The average of these four values was used as a measure of misclassifications and true disagreement on latent content from qualitative text.

The rate of change in coding after discussion was used as a measure of validity, regarding how often the raters thought their own codes to be accurate after having been exposed to a range of interpretations. A measure of confidence regarding collected data is not new, as for example Hanea (2017) and Hemming (2018) both incorporated a measure of confidence of individuals who participate in producing estimated data values (Hemming et al. 2018; Hanea et al. 2017). They asked people to estimate four values; data best estimate, bounds around the estimate, and a value for a self-assessed level of confidence. Their measure of confidence gives information about the intrinsic belief of the rater in their own accuracy. In contrast to their intrinsic measure of confidence, we created a more objective measure of confidence that indicates if a rater's data is robust when tested against other raters, based on how often individual raters change their rating. Our measure of confidence gives information on the ability of each rater to produce codes that are unlikely to be changed when ratings and the underlying evidence in the rated text are scrutinised by others. We recorded the frequency of changed ratings after discussion for all raters across all variables. The resulting set of metrics were (see calculations in Supplementary material S4.2):

a) The main rater's average error rate and standard deviation can be used as a measure for the likely validity of the full data set (which is coded by the main rater only)

b) Error rates and standard deviation of individual raters are an indication for the importance of multiple raters by providing insight into between-rater variation in error rates and standard deviations. If most additional raters have a significantly lower error rate compared to the main rater, it can serve as an important warning sign regarding the quality of the data set that has been produced by the main rater.

c) Error rates for the categories within the 23 individual variables, averaged across all raters, can guide interpretation and adjustments of data for further use, such as collapsing categories when error rates are high.

We accounted for two potential sources of uncertainty: (i) frequency of categories and (ii) numbers of additional raters. The relative frequency of variables (*prevalence*) can influence the rate of agreement. The comparison of agreement rates between variables that were frequently encountered, and variables that were rarely encountered during the rating can be difficult (Sim and Wright 2005). We therefore compared the metrics for two-factorial subsets of the data for categories for variables that were coded in more than 50% of the produced codes across all raters (frequent subset) and less than 20% of the produced codes (rare subset). The precision of averaged estimates depends on sample size and number of raters and has been shown to improve with increasing numbers of additional raters (Marcoci et al. 2019; Bonett 2002). We tested for the effect of number of coders by calculating percent agreement for all possible main rater/additional rater pairs and averaged the values for all permutations of one, two, three or four of the additional raters. The acceptable level of agreement depends on the purpose. For important decisions a minimum of 90% is suggested, with 80% tolerable in many other settings (Lance et al. 2006; Nunally 1978).

Recommended thresholds for different agreement rates to pass a reliability test are given in the literature, for example 60% for kappa (Côté et al. 2013) or 80% for

Krippendorph's alpha (Marzi et al. 2024). However, general accepted methods to derive context-relevant acceptable thresholds that warrant drawing conclusions form the data in general have not been established, and the choice of a threshold is always somewhat arbitrary (Beckler et al. 2018; O'Connor and Joffe 2020). Here, we consider a percent agreement of > 80% as acceptable.

Results

We found that group discussion led to a clear increase in percent agreement for all variables (Figure 4. 1), and by implication a higher reliability of the coded findings. This pattern was particularly strong for the variables with a high frequency of multiple, combined entries, like multiple threats, species, socio-economic objectives, type of management or type of sensitivity analysis. More than half of the 23 variables show an initial percent agreement (Step 1) of less than 80%. All variables except *for type of sensitivity* and *species/system* pass this threshold after the group discussion (Step 2), with 18 out of 23 variables above 90% agreement and 6 variables 100%. This means almost all disagreement was resolved through discussion (Figure 4. 1). This was not only the case on average but a repeated pattern through all rounds of coding (Supplementary material S4.3). The improved percent agreement after discussion leads to different conclusions about the reliability of individual variables and categories than the use of kappa or alpha (Supplementary material S4.4), with 8 categories that would fail the reliability test based on kappa, overlooking that most reasons for disagreement were based on unintended mistakes, and an agreement rate of over 90% after these were detected during discussion.

Figure 4. 1: Percent agreement between the average group of four raters and the main rater for 23 variables before and after group discussions for 21 examples after the pilot. The effect of group discussion to remove misclassification and retain true disagreements is clear for all variables. Black dots show outliers while grey dots display all data via jittering. Note that jittering allows to see all points by pushing them apart, in some cases beyond the accurately located outliers in black.

All raters, including the main rater, changed some codes for at least some categories after the discussions, which allowed the calculation of an error rate for raters and variables (Figure 4. 2). These error rates were compared and used as a measure of validity of answers in the full data set. Most variables with a higher average error rate also had a larger standard deviation, indicating that not all raters made mistakes, while the variable “type of sensitivity analysis” showed a high error rate and small standard deviation, indicating that all raters made many mistakes. The main author kept on average almost 90% of their codes unchanged, with a lower average error rate, and smaller standard deviation than the additional raters, indicating good quality of coding.

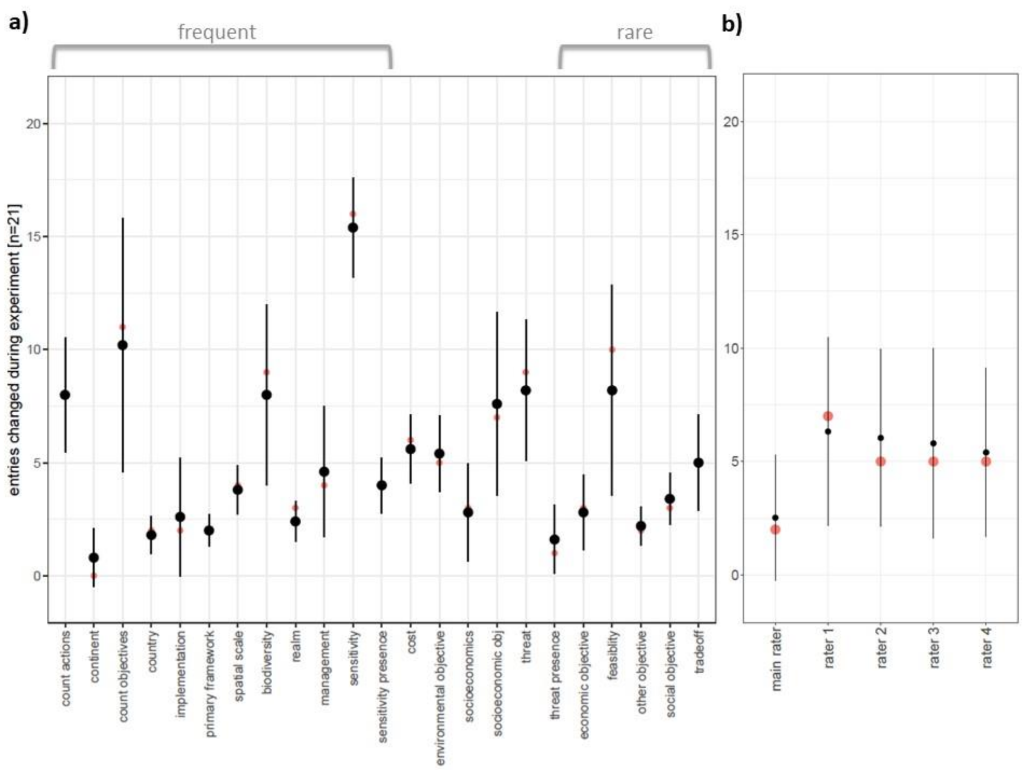


Figure 4. 2: Average and standard deviation of the frequency of unchanged ratings for each variable across all five raters (a) and each rater across all 21 variables (b). Medians are shown in red. Variables that were present in more than 50% of codes were considered frequent, and variables present in less than 20% of codes were considered rare.

Our sensitivity analysis did not find a clear effect of the frequency of different variables (Figure 4. 2). We found a clear effect of the number of additional coders on the rate of agreement when calculating percent agreement across all possible combinations of raters, while calculating kappa across the same combinations of raters did not show any impact of the size of the groups except for increased variance, reflecting the larger number of possible rater combinations to compare to each other (Figure 4. 3, Figure 4. 4 and Figure 4. 5). We also did not find any indication of an improvement of the error rate or rate of agreement over the period of the study.

Most variables would fail the inter-rater-reliability test with the use of Kappa, with many values below the recommended threshold of 0.6 (Figure 4. 3), reflecting the low percent agreement rates before discussion (Figure 4. 4). Identification of unintended mistakes through group discussion led to overall higher agreement rates, in clear contrast to results with kappa (Figure 4. 5).

Figure 4. 3: The calculation of kappa for all possible groups of 2,3,4 or 5 raters did not reveal any impact of group size on pre-discussion agreement.

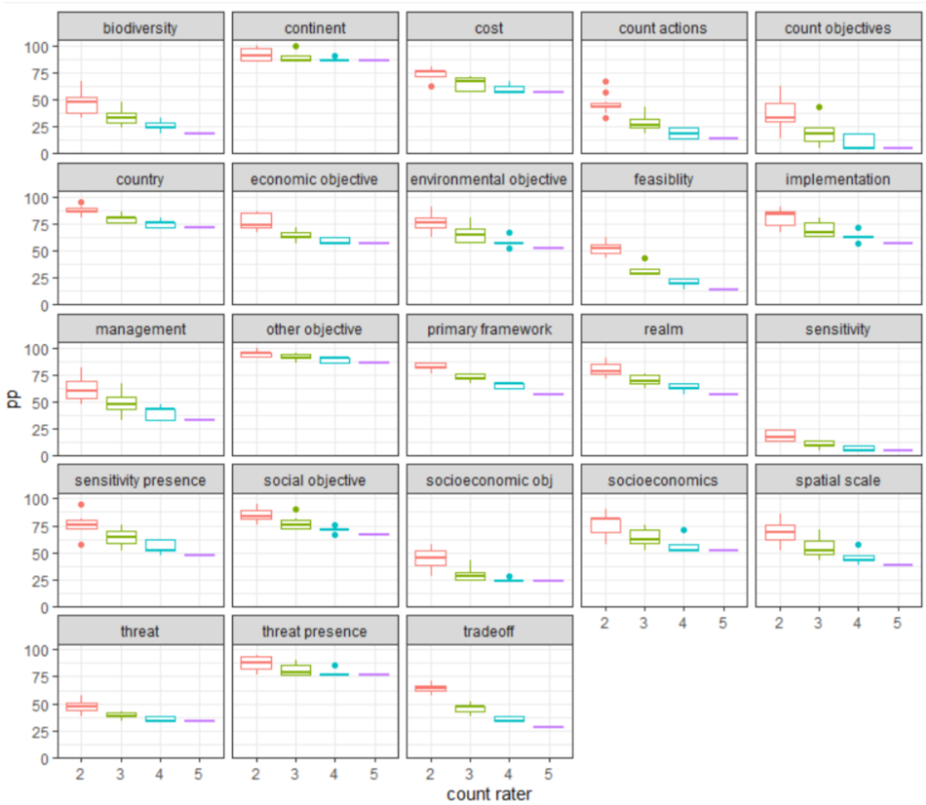


Figure 4. 4: The calculation of percent agreement for all possible groups of 2,3,4 or 5 raters showed that percent agreement was lower for more raters, which is different to findings for coding of quantitative estimates, where the main across all raters is more likely to converge to the accurate value (Marcoci et al. 2019)

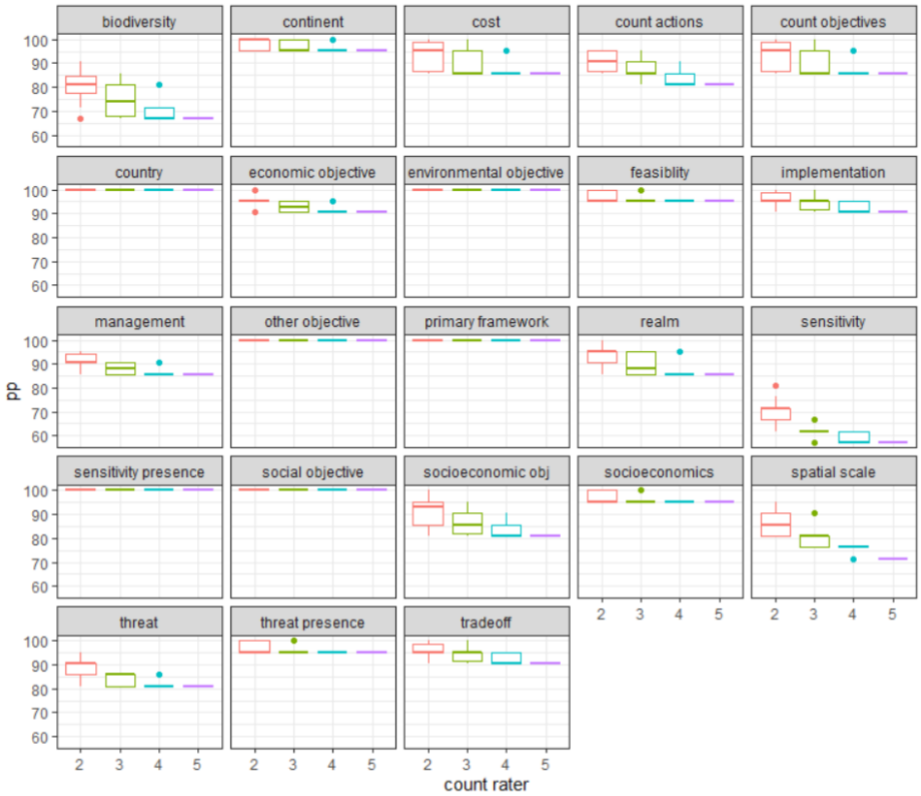


Figure 4. 5: Percent agreement across all combination of raters still shows a negative trend for larger groups after the discussion, albeit with overall elevated agreement rates for all variables.

Discussion

Humans who make judgments on content make subjective interpretations, mistakes, and have biases, as all these are inherent traits of human thought processes. Our experiment shows that this subjectivity plays a large role, as the overall agreement between raters was low before discussions (Figure 4. 1). However, we also found that agreement dramatically increased following conversation, with an average increase in agreement across all questions of 43% (from 45% to 88% agreement) following discussion. In over 50% of cases, full agreement was achieved following discussion. That is because disagreements arising from mistakes or misunderstandings of text were corrected when raters were given the chance to discuss their judgments and underlying reasoning and evidence with others. Discussion resulted in reduced misclassifications but retention of true disagreements. Our method of pilot assessment and calibration through discussion provides an easy and intuitive way to gain insights into the reliability and validity of literature assessments by reducing unintended variability (Kahneman et al. 2021).

What does this tell us about the general process of doing a narrative, search-term based or systematic literature review? Although guidelines acknowledge the importance of testing reliability (Côté et al. 2013; O'Connor and Joffe 2020), they do not go into detail about different testing options, and do not provide guidance on how to stem the substantial additional workload and investment that is usually needed to recruit multiple raters. Strategies of rigorous process, testing categories and training raters are suggested to improve the chance of objectively agreeable judgments. However, our results suggest that finding agreement through conversation is very effective of solving problems including spelling mistakes and oversights, which are unlikely to be overcome with the standard strategies.

Our experiment demonstrates that the opportunity to discuss judgments not only increases agreement between raters but also gives insights into error rates of individuals, which can inform about the rater quality. Science relies on narrative and systematic reviews to build broader understanding of patterns and concepts. Scientists who undertake a review need to be aware of the potential large error rate they might have when judging texts, especially when judgment and interpretation of context in addition to the detection of plain presence of specific words is required. Being aware that review processes are inherently subjective processes should encourage scientists to calibrate their own reliability by exposing themselves and their rubrics to the critical feedback of others during the review process. We all strive for accurate insights when doing reviews, but without the help of others it is not possible to find out if we made mistakes in our judgments.

A reliability-checking process which relies on calculating kappa to see how reliable coding is between raters *but doesn't engage in discussions to interrogate why* *raters might have disagreed*, won't be able to distinguish unintended mistakes from actual, earnest differences in interpretation. Mistakes create unwanted variability on the individual level, obfuscating the detection of legitimate differences in interpretation. Identifying these mistakes allows to detect and address problems, including ambiguities in the coding scheme is ambiguous or difficulty of the rated content.

We therefore believe our method to be better equipped to assess the overall quality of text-derived qualitative literature analysis than metrics that evaluate initial agreement such as Kappa or Alpha which account for chance (Krippendorff 2004). For example, 8 variables that would fail the interrater test by using kappa show over 90% percent agreement rate after discussion, indicating the high rate of unintended mistakes (Supplementary material S4.4). This is particularly the case when ratings are made beyond manifest content (for example coding based on pure detection of specific words) and are subsequently used for quantitative summaries and synthesis of qualitative information. As this is the case for many literature reviews, and these syntheses are highly cited and influential, the additional information that provides a quality-check is worth obtaining.

There were three different types of causes for disagreement: disagreement by mistake, disagreement based on ambiguity in categories, and disagreement by ambiguity in the content that was to be classified. We discuss each of these and implications on reliability and validity in the following.

Mistakes were the most common reason for disagreements, rather than fundamental disagreements of interpretation.

Agreement rates increased drastically after the opportunity to correct mistakes after exchange (Figure 4. 3 and Figure 4. 5). The most frequent underlying causes tended to be forgetting to check tickboxes, entering the wrong code number, and overlooking text. The benefit of discussions to flag mistakes was very clear but time consuming. We were able to improve time efficiency considerably by building some interdependencies and overlap into the coding scheme. Doing so allowed us to check for inconsistencies and flag errors in raters' answers prior to discussions. For example, a question that asked whether socio-economic objectives were present was somewhat redundant given that another question asked raters to identify the "*type of socio-economic objective*" present in the study. But the combination made it often possible to detect missing entries, and raters could be given the chance to fill in their gaps and join the discussion with complete codes.

Mistakes were often caused by difficulties to sustain attention during reading. Coding for variables that required picking up multiple cues in different passages of the text created significant challenges for raters and led to disagreement between raters. For example, there was high agreement between raters about whether sensitivity analysis had occurred in the analyzed texts. However, there was low agreement about which specific types of sensitivity analysis were. In most cases, multiple descriptions of how uncertainties were explored were mentioned throughout manuscripts and there were rarely dedicated concise sections in the analyzed texts. Discussions revealed that the most common cause of rater disagreements for this variable seemed to arise from raters simply overlooking cues within the text, and not from lack of clarity in the writing. This could have been caused by a lack of understanding on the part of the raters about the subject matter in the texts, such that they couldn't discern correct answers from the available cues, or plain mistake by skimming or not focusing enough while reading.

A second cause of disagreement was an inherent ambiguity of categories, when coding categories may be not clear or specific enough such that an unambiguously correct rating exists. Despite inbuilt mitigation via testing codes in a pilot and collapsing problematic categories, some residual ambiguity usually remains. An unfortunate characteristic of classification schemes that are founded on linguistic terminology is an inherent "fuzziness", which results in a lack of clear demarcation between different categories (Sadler 1987), inviting ambiguity. Semantic ambiguity in the available classification options presented to raters can introduce uncertainty and errors in answers they provide. For example, “mangroves” were classified as an individual species, trees, or a type of ecosystem by different raters. In another study, “native woodlands” were classified as forest or ecosystem by different raters, and there were different opinions if “unspecified locations in Victoria” were best classified as local or regional spatial scale, as both interpretations seemed plausible (Rumpff et al. 2011). Although the discussion proved helpful in explaining the underlying cause of disagreement in the case of ambiguous categories, it did not help to resolve disagreement in all cases. Identifying for which variables this is an issue can help to refine the rating scheme and interpret the results.

Our pilot phase of the inter-rater-reliability testing had the objective to mitigate existing ambiguity as far as possible. We expected that we would be able to minimise the issue, but not remove ambiguity completely, due to the inherent fuzziness of linguistic categories. Our results therefore confirm that even though ambiguity in coding schemes can rarely be removed completely, a pilot phase that aims to detect issues can minimise problematic codes.

Some texts were difficult to rate due to under-specificity in the text itself, requiring interpretation of content. Our findings support evidence that different readers package qualitative content in different ways when tasked with classification, despite overall agreement on broader themes (Armstrong et al. 1997).

Some interpretation was easier when raters had advanced knowledge of mathematics, ecology or decision-theory, but some cases relied on purely subjective interpretation. For example, one text described several distinct species and taxa such as waterbirds in the introduction, but it remained unclear if these species were considered in the case study or just used as reference for similar studies (Qu and Lu 2018). The discussion among raters could not clarify if the case study included data on waterbirds, or only broader ecotypes, because the underlying text was not specific enough, and no one could bring forward clear evidence for one case or the other. In a similar example, disagreement remained over whether “non-target species” in a plan for wild pig control were best classified as fauna or not, because although an example with other animal species was given, it was possible to imagine that some of the control activities would have an impact on vegetation (Brondum et al. 2017).

Discussion and identification of frequent mistakes enabled the identification of problematic categories. In our study, seven of the 23 variables were coded with a high error rate, a low initial agreement rate and a higher standard deviation than other variables (Figure 4. 2). Most of these seven variables (species, count of action, count objectives, type of threat, presence of feasibility, type of sensitivity analysis, and type of socio-economic objective) were more difficult for some raters than for others, although a general underlying cause for the divergence in rating is hard to determine. The exception is the variable “type of sensitivity”, which can be identified as the only variable that was difficult for all raters, indicated by the high change of mind and low standard deviation. Collapsing categories can sometimes be the only solution to accurately code such a problematic variable. For example, it was often the case that raters had only detected a subset of the evidence in the texts regarding the variable *type of sensitivity analysis* and realized, once made aware of relevant descriptions in the text, that they had not paid enough attention and needed to add missing categories to their ratings, which led to high agreement after discussion. Another example was the broader agreement that uncertainty has been explored in one of the texts (Wilman and Wilman 2017), but raters could not settle on one classification for the relevant parts in the text as different interpretations seemed plausible to choose the category of different values of parameters, different models, scenarios for different actions, differences of given scores, or a combination of these methods. The reduction to a presence/absence code when disagreement affects only nuances within a specific variable can serve as a more cautious and reliable replacement, albeit incurring a loss of information.

The main benefit from comparing different raters' error rates was to be able to make a judgment on the coding quality of the main rater. The main rater coded a much larger number of texts that could not all be included in a parallel coding stream due to time and cost constraints. But the comparison of error rates gave confidence on the untested codes, because on average all additional raters had a similar error rate and changed their codes more often than the main author. In the hypothetical case that the main rater has a higher error rate, this information could flag concerns about the quality of the codes. In the case that there is no main rater, and different raters code similar fractions of the sampled texts with some overlap, our method can identify raters that perform worse or better than others. This helps to make a judgment on the reliability and quality of the produced codes. If variables are detected that have high error rates in all combinations of raters, categories can be collapsed or dismissed. See Supplementary material S4.1 for examples of collapsed categories in our study that were identified during the pilot phase.

High heterogeneity of qualitative content in papers, as was the case in our study, makes it difficult to create the opportunity for training and learning. Training and learning ahead of rating have been important and well-proven mechanisms to increase accuracy of ratings for quantitative estimations (Wintle et al. 2013). The rationale that training can prepare sufficiently for rating procedures and a time and budget intensive discussion after rating is therefore not necessary might be used as an objection to our proposed method. In the context of quantitative estimates, learning occurs more readily when quantities are repeatedly estimated in a consistent problem context, such as assessments of symptoms of a particular condition in health, or assessments based on quantitative ecological or economic data (Klein et al. 2017; Wintle et al. 2013). In these settings, multiple rounds of feedback on estimated quantities enable raters to calibrate themselves through learning.

However, there are important differences between quantitative and qualitative codes, especially when content that needs to be rated is very heterogeneous.

While the repeated activity of estimating quantities seems a straightforward method to hone a specific skill, the required concentration to read long texts and pay attention to multiple qualitative categories and variables to look out for is a very different challenge. Our results have shown that most disagreement stems from a lack of focus and careless mistakes, and very rarely from a misunderstanding of key concepts or lack of knowledge that could be bolstered through training. A decreasing error rate over time would indicate that raters improve in accuracy by doing the same task repeatedly over time. While evidence has been collected to back up training as a tool in quantitative estimates (Burgman et al. 2011; Wintle et al. 2013), we could not detect such a decrease in error rates and therefore cannot confirm that raters improved coding of nominal variables beyond manifest content by coding the same categories repeatedly over time (Supplementary Material S4.3). We also did not find that agreement was impacted by the frequency with which a variable was encountered. We interpret this as further evidence that training exercises with very heterogenic data might be suboptimal compared to group discussions.

The lack of clear demarcation between classifications might also play a role in explaining why we could not detect any evidence of learning in the form of improved accuracy over time, even though some texts dealt with similar conservation context regarding specific groups of animals or threats. If the heterogeneity of the examples diminished the chance to improve rating through learning, this has wider implications: Any commonly employed preparatory exercises or training before the actual rating will be much less effective in improving the overall quality of the codes than discussions during the rating. This is in line with evidence that outcome based feedback does not necessarily improve the accuracy of ratings, while group based judgment for quantitative estimates seems to be more accurate and reliable than individual judgments (Wintle et al. 2013).

Because of the assumed difference in underlying cognitive mechanisms of rating quantities (a skill that can be trained and calibrated) and detecting cues in text (which depends on prolonged concentration and attention to detail), we believe there are also differences in dealing with the collected quantitative and qualitative data. A commonly used strategy for dealing with divergent rater assessments in expert elicitation and modeling contexts is to compute answer averages (Burgman et al. 2006; Marcoci et al. 2019; McBride et al. 2012; Speirs-Bridge et al. 2010; Burgman et al. 2011; Hanea et al. 2018). Unfortunately, qualitative categories do not lend themselves to averaging due to their fuzziness.

Although errors in codes of qualitative categories cannot be smoothed out through aggregation as it is the case for quantitative estimates, a non-mathematical smoothing effect might be produced through the sharing of arguments and evidence, which enables raters to adjust their best attempt for choosing a fitting variable category code (Wintle et al. 2013). The difference between quantitative and qualitative content might also explain why we found a decrease in percent agreement with increasing group size, which is the opposite effect of numbers of raters on agreement in Marcoci et al. (2019). While our study investigated latent pattern content (detection of presence in context), Marcoci et al. investigated projective content (assessment/judgment of quality expressed through ordinal scales), which has more similarities to quantitative data and can benefit from mathematical smoothing effects.

Caveats of this study

Limited number of examples and qualification of additional raters

When using the difference in error rates as an indicator for the reliability of the main rater, results will depend on the quality of the additional raters. Additional raters need to have sufficient education to understand the task and the content of the texts, and the necessary rigor for a successful rating experiment. In our case study, three raters were in the mid or end phase of their Bachelor's degree, and one rater was in in the final stages of their Master's degree. The main rater was a PhD candidate. It is reasonable to assume that the main rater will likely have spent more time reading and thinking about the question and the coding scheme, as well as being emotionally more invested in a quality result. However, it is also reasonable to assume that more senior scientists that fit the profile for an additional rater for the coding task might be less often available and interested in taking part in such a time intensive and poorly paid exercise.

The limited number of our sample of 25 coded examples gives evidence of how time and budget intensive an orchestrated group discussion is. We used available funds (~AUD 10.000) as a primary stopping rule and all raters were paid for individual coding and discussions with a standard hourly rate until the money was used up. We therefore believe the limited sample size of 25 can be justified in light of budget and time constraints (Simmons et al. 2011).

Additional aspects of inter-rater-reliability were not explored here but might provide further insights.

The agreement within the group of additional raters relative to the main rater's code can be used as a guide to quality. Variables that show high agreement among the group of additional raters and low agreement between individuals and the main rater could indicate problems, while variables that show high agreement among the group of raters and high agreement with the main rater could be used as a general sign of quality (see Figure S3. 1).

Our study does not address the challenges and possible solutions to coding mistakes and uncertainty for manifest or projective content. Future studies could seek to clarify whether multi-rater discussion and calibration improve the quality of reviews based on such data. We would anticipate that whenever the production of codes involves any type of judgment and prolonged focus, there is a strong potential to reduce mistakes and improve validity of codes through discussions of underlying assumptions and reflection on the strength of evidence provided by raters.

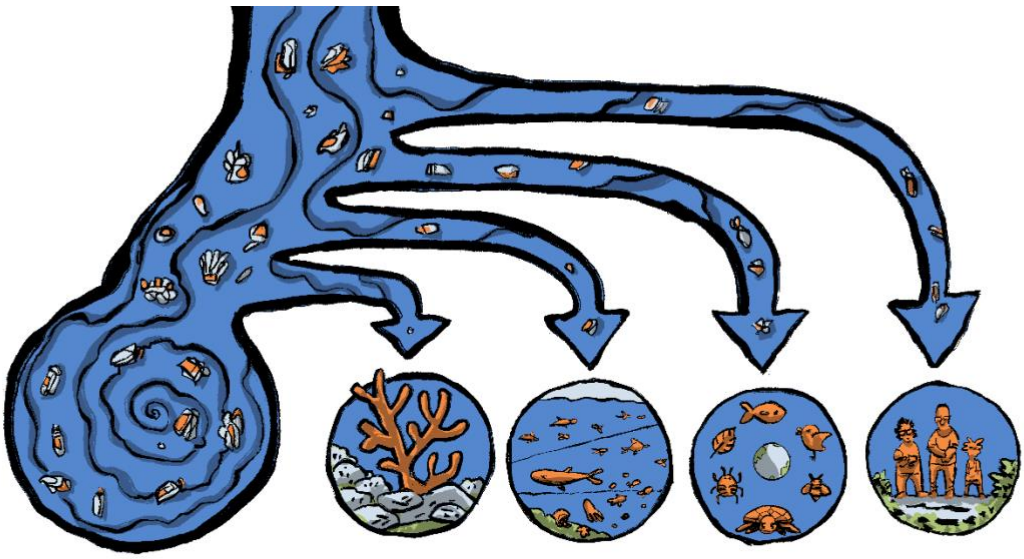
We were not able to examine effects that different media can have on reading and focus, with clear advantages of print media for comprehension and focus (Delgado et al. 2018; Dillon 1992). While future studies could test the effect of reading medium on agreement rates, our results are an important reminder to any academic that comprehension of texts requires prolonged focus, and mistakes that lead to poor comprehension of content can easily happen, even for seemingly obvious things like species, methods and countries included in a study.

Conclusion

Our work provides further evidence that extraction of qualitative data from free-flowing text is a demanding task and benefits from the attention of multiple people. Discussion improves agreement when multiple people interpret the same text by reducing mistakes. The positive effects of discussion on rates of agreement and patterns of error rates were clear and consistent across all variables and raters.

Chapter 5

Decision-science navigates trade-offs between environmental and socio-economic objectives for marine debris mitigation



Abstract:

Marine litter is a growing global problem that impacts biodiversity and human societies alike. Southeast Asia in particular suffers significant impacts due to high biodiversity, dense human populations, and large volumes of plastics entering the marine environment, primarily through rivers. Effective planning identifies the best options to reduce plastic exposure to species, ecosystems, and human populations in the marine and coastal environment, as well as an overall reduction of drifting plastic debris in the open ocean. We show how a structured decision making (SDM) approach can justify and improve site selection for marine debris management. SDM draws on decision-theory principles to navigate complex management problems. We quantify benefits for environmental and social objectives across 542 locations covering 683 rivers along the coasts of Southeast Asia in the biodiversity hotspot of the Coral Triangle. We modelled and quantified metrics for the reduction in volume and flow of plastics to all downstream coral reefs, key biodiversity areas, marine protected areas, and coastal communities. In our analysis, no location is the best option across all objectives, but the multiple metrics help to navigate trade-offs across specific objectives. Despite 95% of all plastic debris remaining in circulation in the seascape after two months, several rivers contribute not only large volumes of plastic debris to the overall marine pollution but also large volumes of pollution downstream. This new decision-science approach for identifying efficient spatial management strategies for plastic clean-up is transferable to any geography and has the capacity to enhance local-to-global plastic management.

Introduction

Plastic debris in the aquatic environment is a growing global problem. The current levels of financial costs of marine debris to national economies are significant and create an urgent need to find ways to reduce the impact of plastic pollution (McIlgorm et al. 2020). Damages from marine plastic to the economies across the Asia-Pacific have risen from an estimated US $1.3 billion in 2009 to US $10.8 billion in 2015 (McIlgorm et al. 2020). Losses of ecosystem services linked to marine plastic debris are estimated to be around 1-5% per year, which translates to $ 3300 to $ 33,000 per tonne of debris, or $500 – 2500 billion per year (Beaumont et al. 2019).

Plastic debris has been detected at every depth, from the surface down to the sediments of rivers and oceans (Barrett et al. 2020; Bauer-Civiello et al. 2019; Cable et al. 2017; Choy et al. 2019; Lebreton et al. 2017; Williams and Simmons 1997). Plastic debris entering the sea generally consists of a mix of micro and macro debris, with all pieces degrading over time (Chubarenko et al. 2020). All size classes of marine debris have the potential to interact with species and ecosystems, including injury and death (Avery-Gomm, Jennifer F Provencher, et al. 2018; Avery-Gomm, Jennifer F. Provencher, et al. 2018; Duncan et al. 2021; Fossi et al. 2014; Hall et al. 2015; Horton et al. 2017; Lamb et al. 2018; Pinheiro et al. 2023; Wilcox et al. 2015; Wright et al. 2013). In addition to the direct impact of plastic debris, there is a range of indirect impacts on ecosystems and species (MacLeod et al. 2021; Rech, Thiel, et al. 2018; Rech, Borrell Pichs, et al. 2018), and social values, including ecosystem services and human health (Beaumont et al. 2019; Campbell et al. 2019; Danopoulos et al. 2022; Ragusa et al. 2021).

Plastic production and pollution caused by mismanaged waste are projected to increase dramatically by 2030, resulting in over 6.3 billion tonnes of plastic waste being produced (Borrelle et al. 2020). Of the 20 million tonnes of plastic debris currently entering aquatic systems annually, 1.15 to 2.41 million tonnes enter through river systems (Borrelle et al. 2020; Lebreton et al. 2017). Active waste removal will remain essential to mitigate the impact of plastic debris leaking existing waste management streams into terrestrial and aquatic environments. However, there are limited resources to implement plastic waste removal, so understanding where the most effective places are to deploy removal efforts is essential.

Many studies quantify the volume of plastic debris that enters the aquatic environment (Borrelle et al. 2020; Geyer et al. 2017; Lebreton et al. 2017) and identify where it accumulates within the water column (Hardesty et al. 2017; Reisser et al. 2015; van Sebille et al. 2020; 2015). Other studies address the processes of prioritizing the locations to remove large volumes of debris from the open ocean most efficiently (Sherman and van Sebille 2016). However, understanding the pathways from the source to the downstream sites where pollution impacts biodiversity and society is an emerging important field of research (Tessnow-von Wysocki et al. 2023). Despite promising first publications (Compa et al. 2019; Critchell et al. 2019), much more work is needed to include all relevant components of the problem. To better manage the plastic problem, we need the capacity to predict the entire plastic pathway, from the source of plastic debris entering the environment to the various downstream habitat destinations where the ecological and social impacts arise. Currently, no framework exists to quantify the predicted inflow of plastic debris to specific habitats downstream of the source of debris when selecting places for clean-up actions.

National governments, non-governmental organisations (NGOs) and local communities need to identify locations where the removal of plastic debris is feasible but also where the investment of time and budget are well justified. In many regions, thousands of locations can be selected for clean-up activities across the considered seascape. Assessing them all in detail is not possible, and often specific criteria are used to narrow down the options in a strategic way. Most plastic removal projects base their clean-up site selection on local characteristics, such as the existing volume of debris, the likelihood of waste mismanagement, local economies, and the level of support and motivation of local government (for example, https://plasticbank.com, https://theoceancleanup.com, https://ghostdiver.com, https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup, https://seabinproject.com, https://cleancurrentscoalition.org, https://www.tangaroablue.org, https://marinedebris.noaa.gov/our-work/prevention, https://cleancurrentscoalition.org).

Unfortunately, none of these efforts use a formal prioritization process based on sound decision-theory criteria and therefore lack the ability to consider the trade-offs between different objectives. A strategic site selection process that draws on insight from decision science can maximise positive outcomes for the environment and communities while minimizing costs (time and money spent). A well-designed site selection process can also capitalize on spatially explicit planning, robust decision science, and transparent risk analysis (Burgman 2005; Moilanen et al. 2006; Sarkar 2012; Sherman and van Sebille 2016; Widis et al. 2015).

The framework of Structured Decision Making (Gregory et al. 2012) has been developed to guide difficult decisions for environmental management and addresses many shortcomings of ad hoc prioritization procedures (Game et al. 2013). The framework is also one important strategy to overcome the barrier of uncertainty when trying to inform policy (Rose et al. 2019), offering distinct steps that provide a transparent process of value-driven prioritization (Figure 5. 1). In this paper we apply Structured Decision Making and spatially explicit plastic debris modeling to achieve three main objectives:

1) Demonstrate the power and utility of Structured Decision Making in aiding in the marine plastic debris problem,

2) Create novel and quantitative metrics for evaluating the impact and feasibility of active debris removal, and

3) Illustrate this approach across the Southeast Asian seascape characterized by high biodiversity, dense human population, and high volumes of plastic pollution.

Our research provides a blueprint on how to conduct a value-based site selection process for marine plastic mitigation, including multiple social and ecological objectives and navigating trade-offs and co-benefits (Halpern et al. 2013; Keeney 1992).

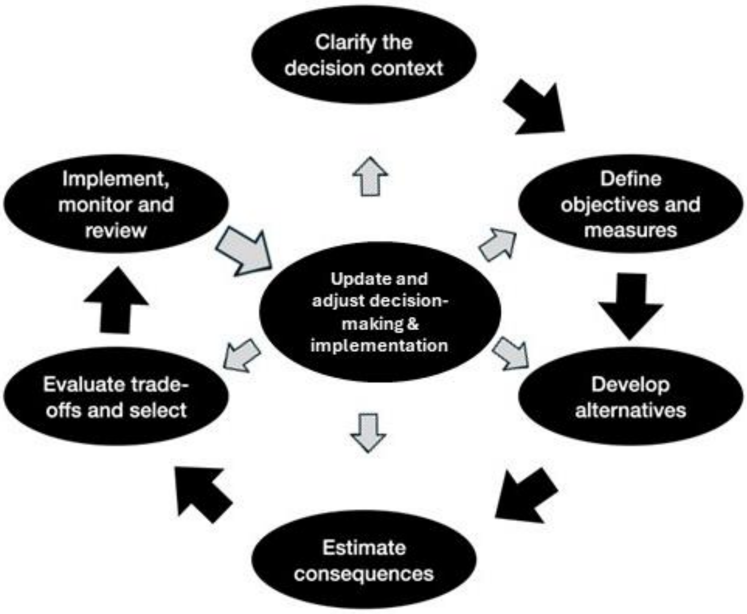


Figure 5. 1: *Structured Decision Making follows a stepwise planning strategy with the potential to feed gained insights back into future decisions of the same type. Adapted from Gregory et al. (2012).*

Methods:

We apply the six steps of Structured Decision Making (Figure 5. 1) to the problem of prioritizing sites for removing plastic debris before it flows into the sea. Below, we briefly describe each step of our application of SDM and then provide more details in subsequent sections.

1: Scoping of the decision context

We expand the scope of current mitigation strategies that focus on volume reduction and include a focus on the downstream impact from specific sources. Our study is in South East Asia, a global population, pollution and biodiversity hotspot. Over 90% of the global plastic discharge from rivers into the ocean comes from 122 rivers, of which the vast majority are located in this area (Lebreton et al. 2017). Southeast Asia has also been identified as a global hotspot of oceanic plastic accumulation (Onink et al. 2021). The seascape around the Coral

Triangle and the shoreline between the Bay of Bengal and the East China Sea (Figure 5. 2) is exceptionally biodiverse (Roberts et al. 2002). The population density in Asia is higher than in other parts of the world, and many Asian countries receive plastic imports from the international plastic waste industry, despite an often problematic waste management situation (Liang et al. 2021). The combination of large volumes of debris, high population density and high biodiversity creates the potential for high negative impacts. Conversely, there are also significant opportunities for interventions such as clean-ups, as well as likely trade-offs or co-benefits between environmental and socio-economic objectives. The UN listed the exploration of plastic debris trajectories within the seascape as one of the key challenges for the coming years. Furthermore, the movement and fate of plastic debris have emerged as one of the five most important research priorities for Stakeholders in Southeast Asia, along with environmental and socio-ecological impacts, possible solutions, description of pollution and regional policies (Omeyer et al. 2022).

Our methods provide a quantitative overview of the key trade-offs for possible clean-up locations, helping to navigate the different benefits for ecological and social objectives and the political feasibility of implementation based on the geopolitical locations of source rivers and receiving sites (Galaiduk et al. 2020). Intercepting debris at a place with a small spatial footprint, like a river, is more cost-effective than targeting debris that has already reached the ocean (McIlgorm et al. 2020). As a result, The Clean Currents Coalition has launched an investment of 11 million dollars for trialing different methods to remove debris in nine rivers around the world (Silva et al. 2021), four of which are located in Asia.

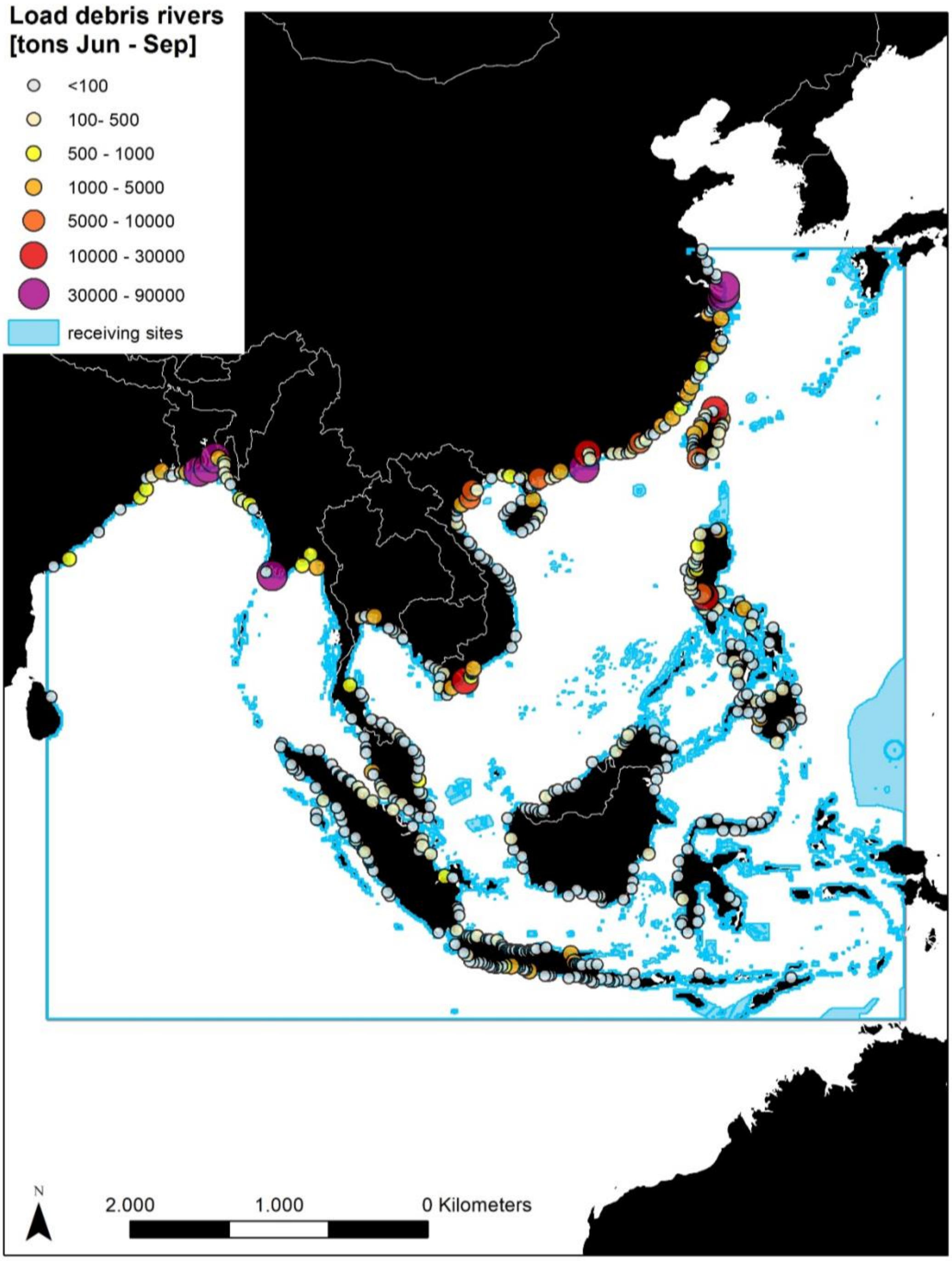


Figure 5. 2: Model domain in the Indian and Pacific Ocean. Receiving sites were delineated using available spatial data for coral reefs, marine protected areas, key biodiversity sites, and general coastline (UNEP-WCMC and IUCN 2021; UNEP-WCMC et al. 2010; Birdlife International 2020). Volumes of plastic debris in rivers (symbolized by points) were summarized from Lebreton et al. (2017).

Communication during the scoping phase of this modelling project validated the relevance of metrics and objectives for agencies that plan and conduct debris removal actions (personal communications with staff from Benioff Ocean Initiative and associated partners).

2: Defining objectives and metrics for site selection of mitigation actions

Clear and quantifiable objectives are essential for a targeted risk reduction of exposure of plastic debris to society and biodiversity. Candidate performance measures need to capture two relevant aspects of impact of a hazard like plastic debris, the type and the risk, in a clear and quantifiable way. The hazard type includes the presence of people and biodiversity that are susceptible to a negative impact at these sites. The likely exposure risk accrues from the volume of plastic debris and the passive transport routes from the river mouth to downstream sites.

Value-based objectives

The development of all relevant objectives requires the consultation of key stakeholders in order to understand the values that matter in the decision-making process (Gregory et al. 2012; Keeney 1992). For example, communities likely value the onsite benefits of reduced exposure to plastic debris in their direct vicinity. However, NGOs and governments might also value comparing local impacts and ensuring equity across a larger region, and considering the feasibility of clean-up interventions as well as likely impacts downstream.

Here, we assume that the reason to mitigate marine plastic debris is to prevent a negative impact on both biodiversity and human society, while acknowledging that the feasibility of local clean-up interventions will vary for technical and political reasons. As a result, these assumptions require the development of multiple objectives.

Biodiversity is seen as valuable for its intrinsic value as well as its contribution to people in the form of ecosystem services. We defined ecological value through biodiversity and conservation-related features, such as species or habitats that are known to suffer negative impacts from plastic debris, in particular coral reefs, marine protected areas and key biodiversity areas. The related objective is to reduce the impact of plastic pollution on the currently existing features.

Demographic groups that live in polluted areas and depend on subsistence fisheries are particularly at risk of a negative impact of plastic debris on health and well-being. Large parts of the population in the Coral Triangle and Southeast Asia depend highly on coral reefs (Burke 2011). Therefore, we quantify social value using population density as a proxy (Center For International Earth Science Information Network-CIESIN-Columbia University 2017). The related objective is to reduce the impact of pollution for as many people as possible.

Regarding technical and political constraints, we included two aspects of logistics: 1) minimise the number of rivers that would need to be cleaned to reduce the volume of inflowing plastic debris and 2) minimise the political complexity related to the number of jurisdictions that are exposed to plastic pollution from a particular source (Galaiduk et al. 2020).

Based on these assumptions, we adopt the objectives of "maximise the benefits (for each of the socio-economic and environmental metrics), while minimising the constraints (feasibility-related metrics)" to identify source rivers where management actions and clean-ups could be implemented. We developed multiple metrics to capture the important nuances of these objectives.

Metrics for impact and feasibility

The contribution of clean-up actions towards our different objectives depends on how the impact is measured. We developed multiple metrics to capture the nuances of site-specific impacts of different clean-up locations at the source (Table 5. 1). For site-specific impact downstream, two metrics of pollution were used: reduction expressed in total volume and expressed as a percentage. Both are needed to make an informed choice of relative benefits that a local clean-up intervention would provide. For example, when comparing two options that reduce the same amount of downstream pollution, the percentage can inform if the difference is likely of broader social and ecological relevance. At the same time, when two options provide the same percent reduction at a downstream site, the amount of volume can identify the more valuable option. As a transparent benchmark, we considered downstream impact within two months of plastic release, acknowledging the potential long-term benefits of reducing the volume of plastic debris at the source.

In summary, trade-offs are expected between the precent reduction and total volume of reduction of pollution impacting individual downstream sites, the sum of all reduction across all downstream sites and the reduction of total plastic entering at the source. To quantify the magnitude and type of impact that a management action can have, and identify key trade-offs, we investigated fourteen different metrics across four objectives (Table 5. 1).

Table 5. 1: Performance measures for different objectives that were utilised to compare the impact of different actions and identify key trade-offs.

Objective	Metric	Subobjective (habitat types)
General impact statistics	[t] Impact at source river, see Eq4 in section 2.4	
	[t] Downstream impact across all sites, see Eq3 in section 2.4	
	[%] Fraction of the river load that pollutes sites across system	
	[n] Sites impacted by this source	
	[km^2] Area impacted (across all sites)	
	[n] Sites this source is the main source of pollution	
Impact for environmental objectives	[t] Volumetric impact downstream, see Eq2 in section 2.4	Reef
		KBA
		MPA
		Coast
	[%] Reduction in pollution across sites & area, see Eq1 in section 2.4	Reef
		KBA
		MPA
		Coast
	[n] Sites with reduced pollution	Reef
		KBA
		MPA
		Coast
	[km^2] Area with reduced pollution	Reef
		KBA
		MPA
		Coast
Impact for social objectives	[n] Impact of a river on number of people within 8 km^2 vicinity	
	[n] River as main source of pollution for number of people within 8 km^2 vicinity	
Feasibility	[n] Technical feasibility: number of source rivers with large contribution to site pollution, width of estuary	
	[n] Political feasibility: number of EEZ impacted	

The exact method to calculate more complex metrics is described in section "*Estimate consequences of alternative management actions with a plastic transport model*".

3: Develop realistic alternatives

Across our study area, we use all major river mouths as potential plastic sources and management opportunities. We only included major rivers with a minimum input of 65 tonnes per year (Lebreton et al. 2017) to justify investment in long-term management (Benioff Ocean Initiative 2019), which resulted in 683 rivers in the region included in the model. These 683 rivers are estimated to discharge 700,000 tonnes of plastic into the ocean between June and September of each year (Lebreton et al. 2017). These volumes and time periods for all rivers were included in the model. For the Ganges and Yangtze rivers with estuaries wider than 100 km, we divided the discharge among three equidistant points along the estuary to represent the geographic variation in flow. In total, 542 source cells in the model domain contained river mouths with plastic where clean-up interventions could take place resulting in downstream impacts.

4: Estimate consequences of alternative management actions with a plastic transport model

To quantify the consequence of clean-up intervention at all 542 locations, we calculated the 14 impact metrics aligned with our objectives (Table 5. 1) by tracking the passive transport of plastic debris through ocean currents from these source locations through the seascape. We developed a plastic transport model to quantify downstream impact.

The model domain

The model domain (Figure 5. 2) was divided into a grid of 721 x 649 cells with an 8 x 8 km resolution. We used publicly available spatially explicit data on reefs, protected areas and key biodiversity areas to create distinct sites of biodiversity value within the seascape (Birdlife International 2020; UNEP-WCMC et al. 2010; UNEP-WCMC and IUCN 2021). Values for the area of all occurring features (coastline, reef, marine protected area, and key biodiversity area) were extracted for each cell, split for unique combinations of overlap, such as individual features (for example, the area covered by a reef), or any combination (for example, the area covered by a reef within a protected area). Neighboring cells containing the same type of environmental features were aggregated to sites with a unique ID number. We included the general coastline in the delineation of sites as coastal areas function as a general sink for marine debris (Martin et al. 2020; Schernewski et al. 2020). This resulted in 4444 sites that could receive inflowing plastic debris. Of these, 617 sites contained key biodiversity areas, 1047 protected areas, 1701 reef, 2922 coastline, and 10 sites represented the borders of the modeled seascape. We assigned a social value to each site by extracting gridded population density within the boundaries of each site. We added the habitat properties and human population of a surrounding one-cell neighborhood for each individual site to deal with the inherent limitation of cell size and placement of grid cell walls. Because of these limitations, results are not meant to be used at the scale of individual receiving sites but need to be interpreted at a more regional scale.

Plastic transport model

We developed a spatially explicit advection-transport model to quantify the impact of implementing mitigation actions at each of the 542 source rivers on pollution of the source site itself, the ocean, or downstream sites. Our model was based on 1) the location of the rivers as the source of plastic debris, 2) the downstream sites for which inflow should be measured described in section 4.1, 3) the volume of debris that the source rivers discharge into the sea, 4) the characteristics of floating particles, 5) the dates of specific release events and 6) drift time duration.

Over 70% of the debris carried by rivers to the Asian seascape each year gets discharged between May and October (Lebreton et al. 2017). We released a cloud of virtual plastic debris from each source river during each week of the months of June, July, August and September for each year between 2005 and 2015, matching the time frame of the published debris data (Lebreton et al. 2017).

Following the release of the cloud of plastic debris, it was allowed to be transported downstream by ocean currents. We tracked the clouds of virtual plastic debris in three-hourly time steps through the flow field (Treml et al. 2012; 2015; Waruszewski et al. 2018). Whenever any fraction of debris released from a source reached a receiving site, a connection between the source and the receiving site was recorded.

Model parameters of local-scale turbulence and the entrapment rate determined how much debris was caught on downstream habitat patches after a minimum drift time of 12 hours to avoid overemphasis on settlement at the source locations. The entrapment rate included any interaction with wildlife, such as intake or entanglement, or settlement on habitats or beaches. Each simulation was stopped 60 days after the release date, and all debris ending up on downstream sites was tallied. We used a travelling period of up to 60 days to identify strong short-term impacts of pollution. A pilot run indicated travel distances over 2,000 km are possible within this time frame.

Due to uncertainty in the volume of plastic inflow, entrapment rate, and the specific depth of debris in the water column during travel time in the ocean, we performed a simple sensitivity analysis with eight scenarios. Uncertainty around the volume of plastic debris in the source rivers was explored in one scenario for average and one scenario for high model estimates(Lebreton et al. 2017). Uncertainty around the depth of debris in the water column and the entrapment rate is a consequence of the variety of sizes and shapes of different items in a cloud of debris.

The uncertainty around the specific depth of plastic particles in the water column stems from the unknown composition of different sizes and buoyancy of plastic debris items. All size classes, from macro to nano debris, are likely to be present in the rivers at any point in time. In addition, the composition of different size classes will change over time as the shedding of smaller particles is an ongoing process. Knowledge of how particle size and shape determine the floating and mixing behavior of individual units of debris in the water column can inform the choice of ocean current data at a specific depth (Chubarenko et al. 2016; Khatmullina and Chubarenko 2019). This uncertainty was explored with two scenarios: one using currents in the surface only (top 1m), and a second using the top 25m from the HYCOM ocean circulation model (Chassignet et al. 2007).

The uncertainty about how much debris was caught on downstream habitat patches was explored through one scenario assuming a higher entrapment rate of 30% per day likelihood and one scenario with a lower likelihood of 2% plastic settlement per day. The ensemble of eight scenarios produced source-to-destination links of marine debris for every release from every river for all weeks across all years.

Calculation of ecological impact

Based on the output of the advection transport model output, we calculated four metrics related to different strategies of prioritization of clean-up interventions at source rivers (Equations 1-4,Figure 5. 3).

1) Relative Impact (Equation 1)

Prioritize source rivers that contribute large relative amounts of pollution to specific receiving sites by calculating the relative contribution this river made to the total pollution of any specific receiving site.

Eq_1: Relative impact receiving site [%] = inflow from $river_i$ at receiving $site_j$ / total inflow from all $rivers_{i:n}$ at receiving $site_j$ *100

2) Volumetric Impact (Equation 2)

Prioritize source rivers contributing a large volume (metric tonnes) to specific receiving sites by calculating the contribution this river makes to the total pollution of any specific receiving site.

Eq_2: Impact receiving site [t] = inflow from $river_i$ at receiving $site_j$

3) Total downstream Impact (Equation 3)

Prioritize source rivers contributing a large volume to the total downstream pollution across all receiving sites by summing up arrivals across all downstream sites.

Eq_3: Impact across all receiving sites [t] = Σ inflow from source $river_i$ across all receiving $sites_{j:n}$

4) Impact at source and open ocean (Equation 4)

Prioritize source rivers with high load of debris by using available data on loads of plastic pollution in metric tonnes.

Eq_4: Source river pollution [t] = load of plastic debris of source $river_i$

We calculated each metric for the three environmental objectives (reduce the impact on reefs, protected areas and key biodiversity areas). For each source river, we could identify all downstream sites with the occurrence of each habitat type and the quantities of pollution that would accumulate there. Based on this information, we subset and ranked individual source sites for relative and volumetric impacts on each habitat type.

Calculation of social impact

We expanded on the metrics for ecological impact to calculate the expected social impact by discounting Equations 1-3 based on the relative number of people who would benefit from reduced exposure to pollution at each receiving site. Population density data were derived from a 5 x 5 km grid of global population densities and summed up for an 8 km buffer around each receiving site. The size of the buffer equates to an expansion of each site of one additional grid cell into all directions, under the assumption that people in poverty who depend most on fishing and other ecosystem services can access the coastline within 8 km on foot on a daily basis (Burke 2011), and people visit closer sites more likely in their leisure time than sites that require longer travelling. Population density was relativized to the maximum value across sites in the seascape (240.595 people/km2 at one site). The social impact at receiving sites was calculated by multiplying impact metrics for biodiversity at these sites (metrics 1-3 above) by the relative population density within 8 km.

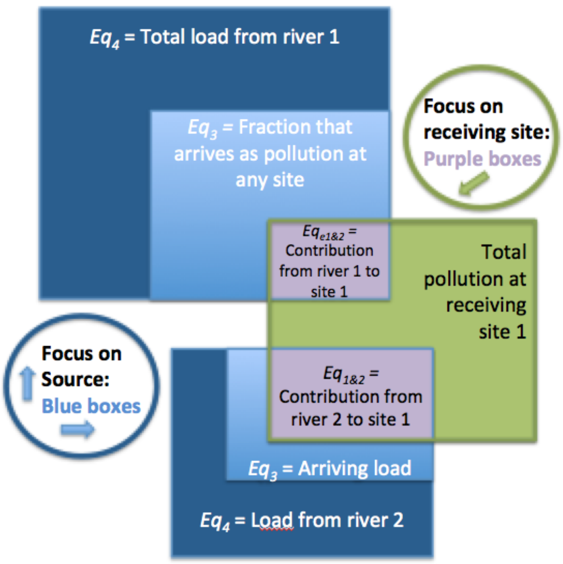


Figure 5. 3: Example of metrics for different strategies to reduce the impact of plastic debris. Current mitigation planning focuses on source-centric metrics, here depicted in blue. Our study highlights the importance of including

metrics for a specific type of impact downstream of the source of pollution. The conceptual diagram highlights that destination-centric metrics will rank sources based on a much smaller fraction of their total pollution load by counting only the volume of pollution accumulating at places of value. Each river is modeled with a specific total load of debris (Eq_4), of which a specific fraction arrives via passive drift at a destination site within the modeled time (Eq_3). Most sites receive debris from multiple rivers. Therefore, the contribution of a river to a specific site can be calculated as the contribution in percent (Eq_1) or volume (Eq_2) of one source to the total inflow of pollution at this specific receiving site.

Feasibility related metrics

To identify which receiving sites were most feasible to manage, we used two metrics: one related to technical feasibility and one related to political feasibility. Regarding technical feasibility, we assumed that the less source rivers need to be cleaned up to reduce the inflowing plastic debris at a receiving site to a desired level, the less infrastructure and resources would be required to establish long-term management for waste removal. Therefore, we used the number of source rivers as a metric for technical feasibility.

We defined political feasibility as the trans-jurisdictional impact of debris dispersal and measured it by overlaying the impacted receiving sites of each source river with a map of the world's Exclusive Economic Zones (Flanders Marine Institute (VLIZ), Belgium 2019). The overlay returned the number of countries that would be involved when managing the source of plastic debris to reduce impact at individual receiving sites, which we used as metric for political feasibility.

We discuss the implications for regional and international management options under the assumption that management for polluted sites is easier when fewer rivers contribute a large fraction of the total pollution at a receiving site and the source is located in the same jurisdiction. For our case study, we used the number of main pollution sources to the most polluted downstream sites in an intermediate step for selecting the most promising locations for clean-up interventions (Supplementary Material S5.3). The number of countries involved in planning and implementing a clean-up at relevant sources was used as a metric in the consequence table assessing the trade-offs between the selection of most promising locations (Table 5. 1 and Table 5. 2).

Summarising impact using Network Analysis

Most metrics needed specific parameters to be calculated, which we produced using network analysis. Our networks consist of a set of nodes representing source rivers and receiving habitats or sites, and all the connections between them representing the volume of plastic flow from sources to destinations. Each scenario returned a set of adjacency matrices that showed a) the probability of a connection between a source node and a receiving site downstream and b) the relative volume of debris that drifted from each source to each receiving location.

The different matrices were used to create the network model depicting the source-destination dynamics of plastic debris across our seascape (Treml et al. 2015; Urban and Keitt 2001). We used the package igraph (Csardi and Nepusz 2006) in the software R (R Core Team 2020) to complete all network analysis (Figure 5. 3, Equations 1-3).

The following parameters in our impact metrics were derived from the plastic transport model:

1) The probability of a connection between a source point (river mouth) and a receiving site. A connection was recorded whenever plastic particles from a source reached any receiving site location. The output is an adjacency matrix containing values for the probability of a connection. This parameter was used in the calculation for metrics regarding downstream impact in volume and percent of pollution.

2) The inflow of all debris from each source river to each individual destination site in tonnes per year. This metric was used to identify sites that receive large quantities of debris from specific rivers. The output was an adjacency matrix containing values for the strength of a connection.

3) The count of how many source rivers contribute to the pollution of each receiving site. The count was produced by summarizing source locations for each receiving site from the adjacency matrices.

For the calculation of feasibility metrics, we derived:

4) The count of how many downstream sites receive inflowing debris from each source river. The count was produced by summarizing destinations for each source river from the adjacency matrices.

5: Evaluating trade-offs to prioritize clean up locations

The set of impact metrics allows an evaluation of the inherent trade-offs and co-benefits between the reduced impact on biodiversity, reduced impact on the coastal population, reduced inflow of debris into the ocean, and feasibility-related characteristics of clean-up sites. In order to evaluate key trade-offs and assess how assumptions and objectives impact the ranking of clean-up locations, we used a consequence table, which is a standard tool within Structured Decision Making (Gregory et al. 2012). The table shows how well the alternative clean-up sites satisfy each objective and metric, highlighting the trade-offs across objectives. We present results from the average modeled flow across all release events in all years, depths, and settlement rates, for the average modeled load of rivers and a drift time of 60 days.

6: Implementation and monitoring

Through the framework presented here, managers across the seascape have the capacity to efficiently identify optimal management actions for reducing the impact of plastics. Although this sixth step is outside the scope of this study, management authorities can use the provided information, maps and concepts to understand the complexity of different options. Once they have made a choice and implemented a clean-up intervention at a site, they can re-enter the decision process with new information whenever monitoring results indicate that the expected benefits are not achieved, enabling a more adaptive management approach.

Results

Sixty days after entering the ocean during each release across all source rivers, the vast majority of the 700,083 metric tonnes of plastic debris remained adrift in the modeled seascape, 34,433 tonnes (5%) had entered receiving sites downstream, and only 641 tonnes had drifted out of the domain. The transport model identified 120,479 individual connections between source rivers and downstream sites with substantial differences in the volume of debris (Supplementary material S5.1).

Ranking source rivers in parallel for each metric highlights not only locations that have a high impact for individual objectives but also those that rank high for multiple objectives. The parallel ranking can quickly narrow down options to a manageable quantity that deliver high impact for one or more objectives (Supplementary material S5.2).

Identifying locations for high impact mitigation actions

The parallel ranking and the comparison of the individual metrics for sources in general and main sources for most polluted sites in particular highlighted several sources for which clean-up interventions could provide large benefits for several objectives. In the following, we provide further detail of the decision process comparing multiple criteria for each of the following options for clean-up locations: the Modaomen Shudao channel and the Yangtze in China, the river Ganges in India and Bangladesh, river Irrawaddy in Myanmar, river Song Hau in Vietnam and river Pasig in the Philippines.

The Modaomen Shudao channel in China (#146) provides co-benefits for all objectives except for the total sum of inflowing debris across all downstream sites. The channel carries the third largest load of pollution in the seascape. The three source points in the Yangtze estuary (ID #195, 196 and 197) and the source points from the estuary of the Ganges (#15, #16 and #17) carry the largest volume of plastic debris (impact at source, Eq4), but are not among the most relevant rivers for coral reefs or overall contribution to downstream pollution (Supplementary material S5.2).

Rivers Song Hau in Vietnam (#95) and Irrawaddy in Myanmar (#29) rank highly for all objectives except for the total sum of inflowing debris across all downstream sites and either Key Biodiversity Areas or Marine Protected Areas. The river Pasig in the Philippines (#255) has the highest rank for impacting coral reefs, both for the most polluted reef site as well as pollution across all impacted reefs, and also ranks high in terms of volume of debris. Coral reefs started to appear from rank 45 of the most polluted sites (Supplementary material S5.3), where a small reef of 2.4 km2 within a site of 320 km2 in the Philippines was polluted by an annual inflow of 159 tonnes of plastic debris by the River Pasig draining into the Bay of Manila. The high value of coral reefs for biodiversity and many coastal communities can be used to justify the inclusion of the most important source of pollution for this ecosystem despite the lower ranking for some other objectives (Supplementary material S5.2).

Mapping the trajectories of plastic debris from all source rivers to all downstream sites shows clear geographical patterns, with several sources standing out that impact the seascape with large volumes of debris over larger distances (Figure 5. 4). Tailor-made maps can help to understand the context for specific objectives. For example, mapping the top 30 sources, pathways, and impacted sites for different objectives (Tables S5.1 and S5.2) highlights differences and similarities between the different metrics (Figure S4. 2) or habitat types (Figure S4. 3).

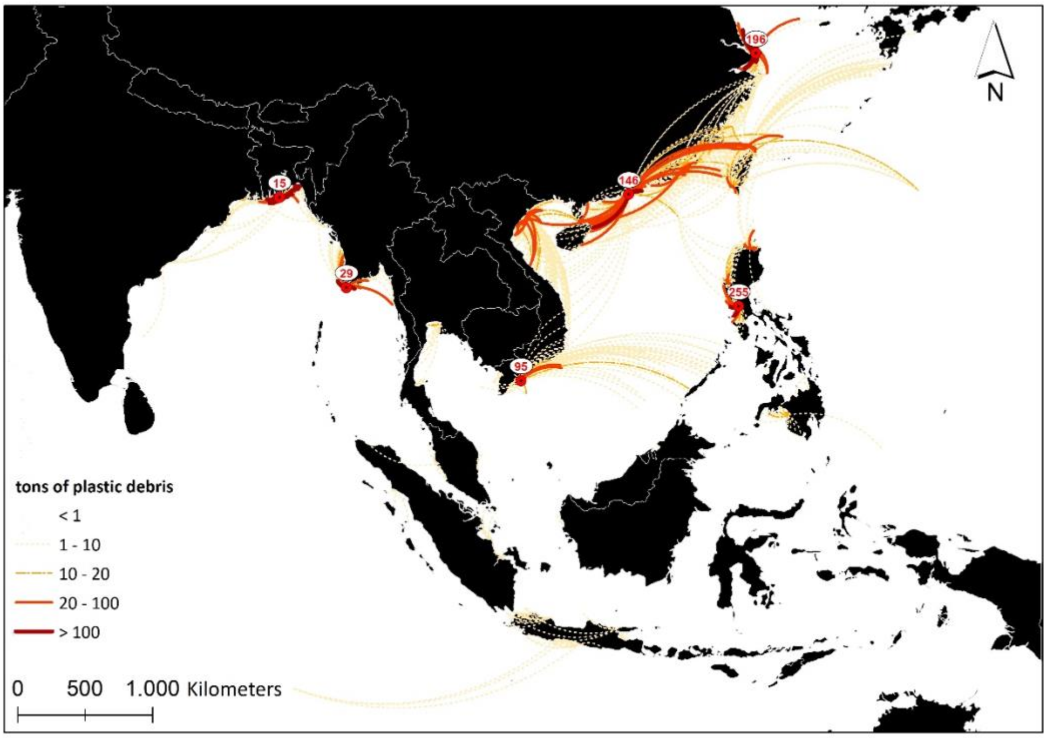


Figure 5. 4: Among the 542 source rivers, only a few stand out that contribute large amounts of pollution to individual downstream sites. Pollution is travelling substantial distances of several hundred kilometers within two months, especially along the coast of China. The six rivers that rank high for multiple objectives are all sources of the strongest pollution trajectories in the seascape, here marked up with their ID numbers. The strong pollution pathways out of the North of Vietnam are attributed to source rivers #123 and #126, which both rank high but for slightly fewer objectives than the six rivers analysed in more detail (see Table S5.2).

The top 30 rivers that carried the highest load of debris (*impact at source*) were distributed in seven countries: the mainland in China, Taiwan, Thailand, India, Bangladesh, Myanmar, and the Philippines (Figure S4. 2, panel a). The 30 rivers that contributed the most to downstream site pollution (*total downstream impact across all sites*) were distributed in five countries because the rivers with high load in India and Thailand were not contributing as much to downstream pollution compared to several additional rivers in China and Taiwan (Figure S4. 2, panel b). The most polluted sites (*volumetric impact*) were strongly clustered along the coast of Myanmar, Bangladesh and China, around the three rivers with the largest loads (Ganges, Yangtze and Modaomen Shuidao channel, Figure S4. 2, panel c). In contrast, the sites with the highest combination of pollution and human density were found throughout the entire seascape (Figure S4. 2, panel d), with some important sources with less total load.

The majority of the 30 most polluted sites for reefs, marine protected areas and the general coastline were located along China's and North Thailand's coast (Figure S4. 2). Important additional countries or regions were the Philippines for reefs, key biodiversity areas and marine protected areas, Myanmar for reefs, key biodiversity areas and marine protected areas, the South of Thailand for reefs, Bangladesh for all but for reefs, Myanmar for all but the general coastline, and India for Marine protected areas (Figure S4. 3). Some sites with reefs, marine protected areas, and the general coastline received high loads from source rivers several hundred kilometers away. For example, #146 pollutes reefs up and down the coastline with more than 20 tons of debris over a distance of over 700km and almost 60 tons over a distance of over 200 km. River 255 has several strong connections to reef sites with a flow between 40 and 117 tons.

Feasibility related metrics: discharge and benefits by country

The Yangtze River (#196) and Modaomen Shudao channel in China (#146), Song Hau in Vietnam (#95), Ganges in India and Bangladesh (#15), Irrawaddy in Myanmar (#29) and Pasig in the Philippines (#255) all impact additional jurisdictional zones, but to very different degrees (Figure 5. 5). The knowledge of international connections between sources of plastic debris and impacted habitats can be a key factor in fostering collaboration and meaningful strategic regional planning not confined by borders.

For example, even though carrying one of the highest loads of debris of all rivers in the seascape, the Yangtze River pollutes only sites within two EEZs, China and South Korea, contributing large fractions to the inflowing debris at multiple sites in both countries (Figure 5. 5a).

The river Son Hau in Vietnam (source ID #95) seems to be a less feasible case to target mitigation actions (Figure 5. 5b), as the pollution from the river gets scattered across ten different jurisdictions, contributing 60-90% of the inflowing plastic debris in many individual sites. Despite the large cuts in pollution inflow, it might not be tempting for Vietnam to invest in clean-up technology when most of the benefit is gained abroad.

Several sites in India receive 60-90% of the incoming debris from the Bangladeshi side of the Ganges delta (source ID #15, Figure 5. 5c). As the Ganges flows through both countries and the estuary stretches across the border, there might be opportunities and incentives for joint investment. If Bangladesh would aim to intercept debris at this specific location within the estuary, it could reap the most benefits within its own jurisdiction.

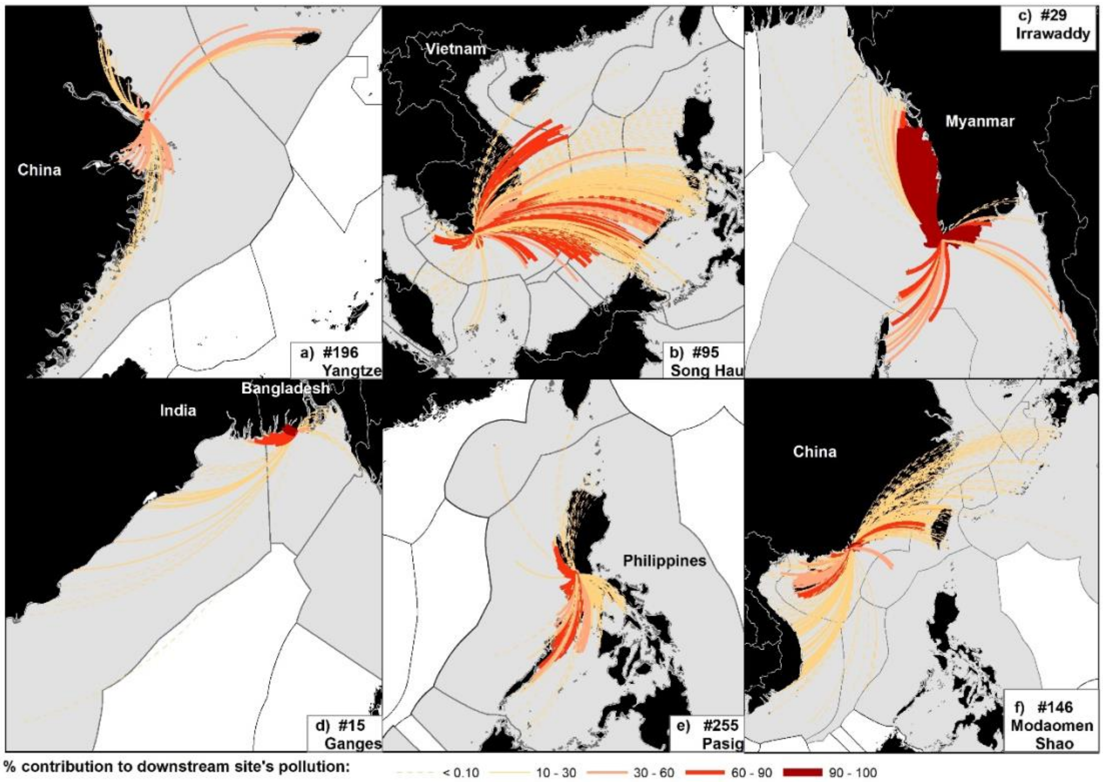


Figure 5. 5: The six rivers that are important for multiple objectives. The Exclusive Economic Zones affected by their downstream pollution are shown in grey. The percent contribution of the total inflow of plastic debris to individual downstream receiving sites can be used to identify how the benefits are distributed across different jurisdictions.

Meanwhile, the Pasig River (#255, Figure 5. 5d), draining into the Bay of Manila, primarily pollutes sites of value within the Philippines' EEZ, with only weak connections to two other EEZs. Therefore, clean-ups at this location might provide a feasible and highly beneficial opportunity for this region to reduce plastic pollution levels for the environment and people.

Highlighting trade-offs with a consequence table

The most promising source rivers for management can be compared across all metrics in parallel to understand the trade-offs for all objectives and type of impact (Table 5. 2). A detailed investigation across all metrics for the six candidate rivers suggests there is no clear best or worst option and therefore requiring managers to make trade-offs based on what they consider most important. River Yangtze carries by far the greatest volume of debris and contributes the largest volume of debris into downstream sites. If reduced at this source, it could cut downstream pollution to all key biodiversity areas by 18% and the general coastline by 15%, yet other source rivers would be better at reducing impacts on coastal populations or coral reefs. The area and number of sites that benefit is

Table 5. 2: Consequence table comparing the top six rivers (columns) and all impact metrics (rows). Detailed benefit analysis for six potential high-impact rivers identified in Table and Figure 5.3. The consequences and trade-offs are clearly identified in this quantitative information on plastic debris pollution at the source and downstream sites for all different environmental and social objectives. Dark blue fields highlight best options, light blue fields highlight second best options for each metric.

	Metric	**Habitat type**	**15 Ganges** (India/Bangladesh)	**29 Irrawaddy** (Myanmar)	**95 Song Hau** (Vietnam)	**146 Modao-men Shao** (China)	**196 Yangtze** (China)	**255 Pasig** (Philippines)
General impact statistics	Eq4: Impact at source river [t]		35,420	31,242	16,893	59,003	82,921	25,992
	Eq3: downstream impact across all sites [t]		1,765	1,460	527	2,945	5,508	1,731
	Fraction of the river load that pollutes sites across system [%]		5	5	3	5	7	7
	# sites impacted by this source		69	110	412	396	95	238
	Area impacted (across all sites) [km2]		32,768	31,104	213,056	163,200	38,656	113,344
	# sites this source is the main source of pollution		18	75	175	82	35	106
Impact for environmental objectives	Eq2: volumetric impact downstream [t]	Reef	<1	232	150	408	2	533
		KBA	1,023	507	52	291	2,331	287
		MPA	1138	227	121	508	634	368
		Coast	1,443	1,401	448	2,791	4,444	1,695
	[%] Reduction in pollution across sites and area	Reef	<1	8	5	14	<1	18
		KBA	8	4	<1	2	18	2
		MPA	16	3	2	4	9	5
		Coast	5	5	2	9	15	6
	# sites with reduced pollution	Reef	2	45	232	103	6	120
		KBA	35	22	35	96	34	27
		MPA	21	8	82	106	23	39
		Coast	65	87	277	333	79	206

	[km^2] Area with reduced pollution	Reef	256	5,039	46,076	22,237	668	35,018
		KBA	5,970	3,391	29,555	33,785	4,309	27,624
		MPA	7,113	5,013	53,262	27,767	5,673	28,032
		Coast	19,441	22,643	92,753	97,204	25,181	53,980
Impact for social objectives	Impact on # of people within 8 km^2 vicinity		1,677,428	335,997	3,455,702	7,615,236	1,671,724	1,970,634
	Main source of pollution for # of people within 8 km^2 vicinity		421,905	155,384	673,479	2,213,270	654,750	846,403
Feasibility	Technical feasibility	Only used for preselection based on downstream sites with highest pollution						
	Political feasibility: # EEZ impacted		3	3	10	9	2	3

also substantially smaller than the area that would benefit from other clean-up options. A clean-up intervention at the Ganges in India could reduce pollution into Marine Protected Areas by 16% (the single best benefit to MPAs) and into Key Biodiversity Areas by 8%. Meanwhile, River Song Hau in Vietnam would be the best option to benefit the highest number of sites (412) and the largest area overall, and also strongly benefits populations. However, these benefits are distributed over ten nations, which might reduce the motivation of the Vietnamese government to invest in clean-up. In addition, the total volume at this source is relatively small compared to the other top-five rivers. Finally, River Pasig and Modaomen Shao channel rank second across multiple social and environmental objectives, as well as general statistics, however, with reduced technical challenges that are expected in the enormous estuaries of the Yangtze and Ganges.

Rivers that are targeted through the Clean Currents Coalition (https://cleancurrentscoalition.org/coalition-projects) include the Assi River (Bangladesh: #9-18), the Song Hong River (Vietnam: #119-127), the Lat Phrao Canal (Thailand: #77-80), and the Citharum River (Indonesia: #441-442). The Assi River is a tributary to the Ganges, which appears in a high rank for all objectives except for coral reefs. However, due to the variability in debris load across the wide delta, it might be a challenging location to create targeted impacts for downstream sites.

Variability of ranks across different model parameters

We assessed the variability in the first 100 ranks based on rivers with high flows to a receiving site (*volumetric impact*, Equation 2), rivers contributing high fractions of the inflowing plastic pollution at a receiving site (*relative impact*, Equation 1) and rivers causing high inflow of plastic debris across all receiving sites (*total downstream impact*, Equation 3) across six ‘sensitivity’ scenarios (shallow and deep currents, high and low settlement rate, mean and high estimates for modeled load of debris in rivers). Ranks based on the volumetric impact were stable across the first 100 ranks (Equation 2, Supplementary material S5.4 top). Most rivers appeared in the first 100 ranks in all scenarios and had low or no variability in these ranks. All six rivers appeared in the top ranks. Variability among ranks based on the relative impact (Equation 1, Supplementary material S5.4 middle) was higher, many rivers appeared only in some of the scenarios in the first 100 ranks, and only one of the rivers we examined appeared in the first 100 ranks. Variability among the first 100 ranks for the total downstream impact (Equation 3, Supplementary material S5.4 bottom) was highest, with most rivers only ranking in the first 100 ranks in few of the scenarios, and none of the selected rivers appeared in these top ranks. The results suggest that planning based on the flow of volume from source rivers to receiving sites might be the most robust metric when considering a range of likely parameters in the model.

Discussion

An important aspect of the Structured Decision Making process is the well-defined metrics that show the nuances of different objectives with a clear and transparent method to navigate the trade-offs between them. As expected, prioritizing different objectives and metrics lead to different priority source sites for management. We found three main types of trade-offs for marine debris management in Southeast Asia: 1) reducing total plastic vs reducing impact at specific downstream sites; 2) reducing the downstream impact on social vs environmental outcomes; and 3) reducing impact per se vs the feasibility (political and technical) of implementation. Each of these main trade-offs are described further, below.

The first trade-off is between reducing the volume of circulating debris in the open ocean vs reducing negative impacts in specific places of value. Within our model, approximately 5% of virtual plastic settles in destination habitat after two months, roughly matching estimates from previous studies, considering that only 1% of marine plastic debris is believed to be bound in surface waters (Eunomia Research & Consulting Ltd 2016). Therefore, targeting clean up at locations carrying a high load to reduce the accumulation of large volumes of pelagic pollution seems to be a reasonable strategy. However, there are trade-offs with the downstream site-specific priorities. Several rivers that carry the highest volumes of pollution do not rank high for many other places or habitats of value. When the aim is to reduce the overall volume of marine debris and plastic pollution in general, regulating production in general seems to be a more feasible approach than trying to intercept large volumes along their trajectories after they enter the environment, as there is a direct correlation between production of plastic and plastic pollution (Cowger et al. 2024). Improvement of waste management infrastructure has emerged as a priority in national policies in the seascape, confirming the risk of repeated leakage of retrieved debris (Arifin et al. 2023). Indeed, the rivers we assessed in detail due to their large benefits for multiple objectives were located in China, Vietnam and the Philippines, which ranked along with Indonesia as countries with the most mismanaged waste material (Jambeck et al. 2015). This introduces the risk that removal of debris is only temporary. At the same time, some rivers that are the main sources of pollution for specific sites or coastal populations are not necessarily among the rivers with the highest load in general, but management of these sites would have additional benefits that go beyond the amount of removed debris.

The second key type of trade-off is between reducing the impact across competing values (e.g., social vs environmental) at downstream sites. A clean-up intervention at river Song Hau would provide some of the greatest benefits to the coastal population as well as the numbers and area of downstream sites, especially coral reefs and MPAs. However, this option provides much lower benefits for more ecologically meaningful metrics such site-specific plastic inflow (volume or percent) than a clean-up at Irrawaddy, Modaomen Shao channel or Pasig. A clean-up at the Ganges would provide the best ecological meaningful benefits to MPAs and KBAs but some of the lowest benefits to reefs and human populations. A clean-up at the river Pasig would provide the highest reduction of percent and volume of plastic debris inflow to coral reefs, but at the same time, provide some of the lowest benefits to key bio-diversity areas and marine protected areas among the assessed options. Despite the necessity for decision-makers to navigate the trade-offs between competing objectives, the transparent and quantitative comparison of consequences makes this decision-making process clear and equitable, enabling a strategic investment into the most appropriate location and action.

The third general trade-off is between the best outcome across all or most objectives regarding downstream benefits versus the most feasible implementation (least political and technical challenges). Two rivers with the highest volume of debris, the Ganges and Yangtze, would be clear priorities, yet provide lower benefits to coastal populations or coral reefs than several other options. These two rivers would also be technically challenging due to their wide estuaries stretching over hundreds of kilometers. However, they should also be politically feasible and tractable as the pollution destinations from these top sources are largely contained within their own Exclusive Economic Zone. In contrast, the source river Song Hau (Vietnam) or Moda-omen Shao Channel (China) contribute plastic pollution to many downstream nations, making the source-destination impact less politically feasible and motivating. Collaborations that account for these types of burden sharing of costs at the source relative to the downstream benefits will be key to achieving impacts on a meaningful ecological scale, as is the case other cross-jurisdictional ecological challenges (Clark et al. 2023).

Implications of our study for identified priorities in the management of marine plastic debris in the Asian seascape

Movement patterns, dispersal pathways, and accumulation zones, as well as their variability, are highlighted as a current important knowledge gap and priority areas of research for marine plastic pollution in Asia (Omeyer et al. 2022). The urgent need to quantify expected impacts on several marine habitats and coastal populations, which could serve as a proxy for ecosystem services and degradation of seafood safety, is identified as another key area of research. Our study does not only provide workable examples and analysis pathways for the identified priorities, we also showcase how a rigorous framework can be applied to identify intervention locations with high impact for a combination of objectives, including the consideration of the geopolitical role of countries. In the following, we put our study in context of several countries.

For example, Indonesia experiences increasing environmental pressures and costs of marine plastic debris in the Coral Triangle and is one of the first nations to have a National Action Plan on marine plastic pollution. However, there seem to be no clear priorities or set processes for the selection of clean-up locations yet, and only few studies have investigated sources and trajectories of marine debris pollution that arrives in its jurisdiction (Purba et al. 2019).

Several rivers in Indonesia have been among the top source rivers of marine plastic debris in different studies (Lebreton et al. 2017; Meijer et al. 2021), and population and consumption growth, as well as severe problems with waste management, predict a worsening of plastic pollution in the future (Lestari and Trihadiningrum 2019). Published modeling for Jakarta suggests outgoing debris floats into the Indian Ocean, while incoming debris comes from Java, Sumatra, Kalimantan and the Gulf of Thailand (Iskandar et al. 2021). In our study, several rivers in Indonesia ranked as high priorities for two objectives (contribution to site pollution and pollution that impacts people).

In Vietnam, only 10-15% of plastic waste gets recycled, with a generation of 3.7 million tons of plastic annually (Veettil et al. 2023). The government is dedicated to reducing the inflow of debris into the sea by 75% by 2030 and banning single-use plastics. The national strategy on marine debris management lists the monitoring and assessment of important sources of marine plastic debris as a key objective (VASI (Vietnam Administration of Seas and Islands) 2020). The river Song Hau in Vietnam emerges as one of the most impactful intervention locations for the largest number of sites and overall area that could benefit from a reduced inflow of plastic debris in our study. Other studies mention mangroves and seagrasses as important sinks of plastic debris. These additional habitat types could be integrated in the same way as the reefs, MPAs and KBAs in our analysis, which might identify additional rivers as a priority for mitigation actions than the ones we identified here (Harris et al. 2021; Veettil et al. 2023).

In the absence of national monitoring data, the national waste management in the Philippines is based on international estimates (Alindayu et al. 2023). Our results indicate that the management of inflow to coral reefs can be managed to a high degree by national actions, for example, intercepting pollution at the river mouth of the River Pasig, which could at the same time contribute to the collection of local data (Alindayu et al. 2023). Manila Bay was identified as the location with the highest accumulation of debris in a recent sampling effort, confirming the modeled hotspot (Gomez et al. 2023).

Thailand relies on mainly voluntary measures, which currently fail to mitigate the growing problems of plastic waste, and the country is not set up to provide commercial plastic recycling facilities (Marks et al. 2020). Transboundary partnerships are key to enabling effective policies and strategic action on the growing plastic waste problem (Marks et al. 2020). Our study showed clearly that not every clean-up intervention at a river with a high pollution load would provide the same direct short-term reduction of debris inflow at downstream sites of value. Learning how to assess direct benefits for different objectives could be an additional motivation for countries to invest in interception technologies at the source and inform international collaboration. Even though we did not explore a particular river from Indonesia or Thailand in full detail, the data and methods provided would make it easy to assess all options in the same way.

Improvements in the decision-making process for selecting clean-up sites

Compared to other methods that offer guidance during multi-objective prioritization procedures for conservation management, such as portfolio theory (Beyer et al. 2018) or Pareto Ranking (Chollett et al. 2022), Structured Decision Making has the advantage that it instructs decision-makers to investigate the information behind calculated ranks. A critical aspect in the context of mitigation options for marine plastic debris pollution is that Structured Decision Making encourages decision-makers to spend time developing a clear scope of the problem and relevant objectives and metrics. Exploring and defining different values and objectives produces relevant information about the different types of impact a clean-up effort can have beyond the removed volume of debris. This process helps to understand that multiple quantitative metrics are needed to fully understand the breadth of potential impacts and the related trade-offs for different clean-up locations. The importance of considering multiple metrics instead of single indicators to capture the different dimensions of the ecological context has been stated in other conservation contexts (Adams et al. 2021; Wyborn and Evans 2021).

The results of our case study highlight for the first time how important deliberation on different values, objectives and metrics is in the context of marine plastic debris by showing that the choice of different performance measures leads to a different ranking of clean-up locations. Our case study provides clear concepts for decision-makers and planners to expand the current predominant focus on removing large volumes of debris by adding considerations on direct benefits to species and habitats downstream. As most species and ecosystems suffer from multiple impacts, reducing plastic pollution might bolster their ability to withstand other threats (Côté et al. 2016).

Constraints and uncertainty

Our study has several constraints for informing site selection for debris management. For informing real-world management, additional analysis would be needed to explore a number of uncertainties, particularly model uncertainty and input parameter uncertainty (Regan et al. 2002; Rounsevell et al. 2021). The three main caveats in our analysis are model resolution, the physics of plastic dispersion in the water column, and plastic debris volumes at the sources.

The choice of data describing the ocean currents influences results because they are the driving force behind measuring trajectories. The first constraint of the HYCOM model is its resolution of 10 km2, which limits detail for the passages between islands throughout the Coral Triangle and does not account for tidal forcing or other small-scale aspects of ocean currents. Reruns with alternative current data in higher resolution would be required to quantify variation in results based on the choice of current data and might also provide better information on the differences we found in trajectories coming from different locations within the estuaries of the Yangtze and Ganges. Particularly for coastal zones, additional exploration of the impact of resuspension rates at beaches and other shallow coastal zones would be needed to explore the robustness of the results.

The second constraint of our model regarding the physics of plastic dispersion includes the considered parameters for movement. While our model includes advection and dispersion, we have not accounted for windage, sinking, settling, beaching, refloating or biofouling and degradation that might change physical properties like size and shape over time, which in turn affect drift behavior (Chubarenko et al. 2016; Khatmullina and Chubarenko 2019; van Sebille et al. 2020).

The third constraint is the reliance on one dataset on debris load in rivers. We could have tested alternative data sets, as done in other studies investigating the settlement of plastic debris (Meijer et al. 2021). Because we wanted to focus our study on the concept, it seemed more appropriate to include a general approach to investigating the robustness of results than adding detailed sensitivity and scenario testing of the chosen models and parameters that have been addressed elsewhere (Jones et al. 2016; Schlaefer et al. 2022; Simons et al. 2013; Treml et al. 2015).

The utility of prioritizing locations for local clean-ups in a global context

Removing plastic debris that has already entered circulation pathways is a temporary and local mitigation strategy and is not comparable to a long-term strategy based on policies and regulations that can reduce the overall inflow into the environment (Bergmann et al. 2023; Cowger et al. 2024). Considering the socio-economic realities of increasing production and high rates of waste mismanagement, the production of new plastics needs to be reduced and regulated dramatically (Diana, Vegh, et al. 2022; Stoett 2022). This is particularly important in countries with high waste exports, such as Japan, the United States or the Netherlands (Basel Action Network 2021). As the problem of pollution is linked to the mismanagement of waste, trade flows are an important aspect of the problem. A contentious report focusing on Asian countries was retracted because the aspect of international trade and hence the actual polluters were not reflected in the methods used, creating a misleading narrative (The Guardian 2022). Illegal trade (Interpol 2020) to countries with high rates of mismanaged waste, such as an estimated 70% for Thailand (Marks et al. 2020), creates doubts that salvaged volumes of debris will not enter the environment again.

An international movement to create a legally binding treaty to end plastic pollution by 2024, along with waste management and regulation, have been highlighted as an important avenue for change in impacted countries such as the Philippines, Indonesia, Malaysia or China (Eisma-Osorio 2021; Kamaruddin et al. 2022; UNEP 2022a). However, negotiations among countries on the exact details of the treaty are slow and influenced by industry (CIEL 2024; Diana, Reilly, et al. 2022; Diana, Vegh, et al. 2022). Despite the initiative, the production, use and disposal of conventional fossil fuel-based plastics are increasing and are forecast to grow to 19% of the global carbon budget until 2040 (Law et al. 2020; UNEP 2022b).

Conclusions

Without more fundamental regulatory measures, any local management focusing on the clean-up of marine debris is likely to be dwarfed by the predicted growing inflow of mismanaged plastic waste into aquatic and terrestrial systems. The growing production and waste streams drastically reduce the expected effectiveness of clean-ups, and the impacts on human health and the environment can be substantial (Human Rights Watch 2022). When collected plastic debris is likely to enter the environment again, a focus on intercepting these trajectories to downstream sites with high social or environmental value gains more weight than just removing high volumes, as removal is likely to be only temporary.

As long as plastics remain in the environment, methods are needed to mitigate the direct impacts of circulating pollution. Our study highlights how Structured Decision Making could be used as a crucial component of future efforts to identify strategies that can coordinate the mitigation of multiple impacts of marine plastic debris. Decision-makers need to be aware of the consequences and nuances of impact between different possible clean-up interventions. The insight into the variability of the most important social, technical, political and environmental consequences of each intervention site demands rigorous thinking, but also offers transparent and logical prioritization. While it is unlikely to identify a clear "best" river to mitigate pollution, the use of Structured Decision Making with explicit investigation of trade-offs will enable a more informative decision process for managing plastic debris in the marine and coastal environment.

Chapter 6

Summary and conclusions

This thesis explored different ways in which judgment-based choices can influence decision-making for nature conservation. Decision-making processes intend to assist people in identifying their preferences by providing a deeper understanding of the factual understanding of the problem context and the values that define the objectives a solution should deliver. As facts (undisputed information with high certainty) can be rare in complex problem contexts, judgment on what seems to be the best available evidence are required, which the decision-making process needs to actively address. Decision-makers base their choices on implicit or explicit predictions of what will happen when any of the available options are picked (Fischhoff and Broomell 2020). To settle on a specific choice, people rely on their judgment, which represents a combination of a person's belief in facts (information rooted in evidence of high certainty about how the world works, including cause-and-effect relationships) and their values (what decision-makers or stakeholders want or care about). They are the basis for choices among available options. The more uncertainty exists either in the understanding of cause-and-effect relationships in the socio-economic system or the specific values that lie behind different objectives, the more assumptions an individual has to make and construct their preferences based on the limited understanding of facts (conveying information that is seen as evidence with high certainty) and values they have (Bond et al. 2008). Decreasing uncertainty in understanding factual context and inner values that inform decision-making helps to identify the most meaningful options. The four chapters demonstrate the vast implications that judgment-based choices within different decision-making steps can have and the possibilities not only to identify and understand these implications but also to include them in a transparent way in the decision process.

Chapter 2 focuses on the choices of parameters to include in an analysis to produce insights into current trends and patterns in available data. Improving the outcomes of conservation science and practice relies on an accurate understanding of the focus and geographic spread of current efforts. Summarizing available data in broad patterns can obfuscate underlying but important nuances. The results in this chapter show clearly how a more rigorous exploration of broad patterns can change the emerging narrative substantially. Perceived global patterns of conservation efforts regarding taxonomic groups need to be tested to be sure that they are not artefacts of smaller subsets of data with strong bias while the rest of the data shows different patterns. The problem has been demonstrated to exist within synthesis reports that explore Red List data, where few species groups drive the overall patterns of decline (Leung et al. 2020), and the theoretical requirements to identify robust patterns from large data sets are well established (Spake et al. 2022).

The identification of a general bias towards vertebrates observed in the published literature on conservation and ecology could be replicated within a large sample of documented conservation decisions, albeit less strong and with several caveats. Upon more nuanced investigation, I could show that the bias is predominantly driven by the large number of studies from the United States, where vertebrates were much more frequent in all contexts of threats, management action, realm and level of implication than other taxa. However, consistent patterns in taxonomy were not observed across other geographical zones. In Europe and Latin America, an overall bias towards vertebrates exists only in some of the many categories I examined. In Africa and Asia, examples of vertebrates were less common than examples of plants.

The results highlight the importance of a more nuanced analysis of broad patterns, especially when the objective is to inform conservation planning and decision-making. More important issues than the strong bias towards vertebrates in North America were the overall geographical bias, with almost 50% of all publications describing biodiversity problems in Australia and the United States and the large number of examples that did not describe a clear threat to justify a specific management strategy. This problem was particularly pronounced in Europe, where 40% of all examples lacked a clearly described threat in the decision process. The most frequently addressed issues were loss of habitat, problematic species, and take, which were the focus in 13-15% of examples each. No threat showed a bias towards vertebrates across all geographic zones. Threats that were less often found overall were among the most prominent in some geographic zones, such as pollution in Europe and Australia or system change in Australia. Over 75% of all examples in Asia, Africa and Latin America describe protected area planning, giving limited insights into planning for other types of management in these geographic zones. Population management is the only management type with a clear bias towards vertebrates across all geographic zones. Terrestrial biodiversity was covered in 60% of all examples, with much less focus on freshwater and marine realms. Gaps of documented conservation decisions were found for freshwater realms in Latin America and Africa, marine realms in Latin America and Asia, applications of decisions from Latin America, and generally low numbers of other management approaches than protected area planning. Translating existing studies from Asian, East European and African countries to English could close some of these significant gaps to better understand global conservation efforts.

Chapter 3 presented a quantitative assessment of the effectiveness of common decision-aiding frameworks and tools to include key elements of decision science when applied in the context of conservation decisions that aim to solve or mitigate a specific environmental problem. My work identified specific differences between the individual applications. These differences in the uptake of decision-theoretical elements in the decision process between frameworks and tools were more evident than differences between applied and academic contexts. We could not detect any clear increase of any framework over the 10-year period (Figure S2.

2). Structured Decision Making, Cost Effectiveness, and Multi-Criteria Decision Analysis studies show more examples in the later 2010s. However, 2017/2018 sees a drop in numbers again, so the trend might rather show a fluctuation around low numbers than an increase. Another key insight was the rather apparent rift between preferences of frameworks in applied and academic contexts. While systematic conservation planning and adaptive management are most frequently used in academic contexts and provide the vast majority of all found examples, applications in conservation practice seem to use more often frameworks than tools (cost-effectiveness and multi-criteria decision analysis) and have a relatively balanced use of structured decision-making, systematic conservation planning, mixed approaches or adaptive management. When considering the uptake of elements from decision science, structured decision-making seems to be particularly successful in a conservation practice context. In contrast, systematic conservation planning provides the majority of examples in academic contexts. Notably, I found documentation of 4 or 5 elements in the documented decision processes in three-quarters of structured decision-making examples but only in about one-quarter of the academic systematic conservation planning examples. The review suggests that publications in the peer-reviewed literature are not, by default, high-quality examples of how decisions should be made, as many important elements are frequently not reported across different frameworks and conservation management strategies in both academic and conservation practice contexts. When guidance on decision-making is required, other sources, such as textbooks that specifically focus decision science and the processes that help people to identify their preferences, might be more trustworthy than a random draw from the peer-reviewed literature. At the same time, the strong geographic bias highlights that many decision-making examples from non-English-speaking countries are not accessible to English-speaking academics. Increased translation in both directions is urgently needed to produce a more complete understanding of decision-making practices around the world.

The review process of the manuscript also revealed the strong and often diverging opinions different scientists have regarding relevant frameworks and tools for decision-making, and the utility of including all relevant criteria in the documentation of a decision process. The interactions confirmed the necessity to think deeply about standards in reporting to make published conservation planning processes repeatable and transparent. A recent effort of a large number of experts in the field calls for exactly that in the field of systematic conservation planning, confirming the identified lack of transparency found in my analysis (Jung et al. 2025). Post-hoc additional searches in the Web of Science regarding some frameworks that different reviewers criticized as missing did not return any examples, indicating, for example, that the open standards for conservation are not visible in the peer-reviewed literature about decision-making, despite their popularity among practitioners. Structured literature reviews that might include additional keywords that could include decision-making processes (but likely as about something else), such as "assessments" or "evaluations", will have to sift through many thousands of additional publications with an uncertain return on investment of time and budget.

Another important aspect the review process uncovered is the widespread misconception of what constitutes a systematic literature review compared to a quantitative, or structured, review. While I have learned the lesson, I hope future PhD candidates and their supervisors will get alerted to the nuances in terminology and the related purpose and required processes of the review work.

Chapter 4 presented a novel method to improve the assessment of the reliability of categorical data that requires a degree of personal judgment. Acknowledging the advantages and disadvantages of purely mathematical or behavioural aggregation of information from several raters, I developed a stepwise protocol to combine both aggregation types for the purpose of coding text from literature to produce qualitative categories and assess the reliability and validity of the produced ratings. In my experimental set-up with four additional raters, I could show that error rates are the primary source of disagreements in a multi-rater set-up and would not be caught without a process that includes review and group discussion. Allowing raters to reflect on their rating in light of other responses reduces not only individual error rates but also provides a measure of the relative quality of raters. Especially in the context of literature reviews with large sample sizes of several hundred publications that need to be read and coded and the common practice to only expose a subset to inter-rater reliability testing, it is invaluable to understand if the individuals that conduct the bulk of the rating have an above or below average error rate. Commonly used metrics such as kappa might overlook the impact that errors can play in ratings, and the identified agreement rates might not reflect the actual agreement among raters nor give insight into the relative quality of ratings from individual persons. Therefore, the developed method might be an intuitive and valuable alternative to the existing suite of reliability metrics. It includes help to reduce linguistic uncertainty in the classification codes (by measuring the rate of change and error in different category codes), improvement of error rates of intended ratings (by updating error rates after discussion for each rater), and insight into residual error rates across raters (by using the difference of ratings before and after the discussion as a measure). Effects of training could be measured with large enough sample sizes and number of rounds.

Chapter 5 presented how a rigorous decision-making framework can be used to improve planning in an applied context. The current efforts to curb the impact of marine debris are largely focused on reporting on volume collected or showcasing specific technologies. In my case study on prioritization of possible clean-up locations in the Asian seascape, I have shown how strategic planning can broaden the scope and integrate several dimensions to the usually narrow problem context. By adding clear metrics for several environmental, social, political and technical objectives, decision-makers have the ability to transparently acknowledge existing trade-offs, enabling them to make informed choices on the likely benefits and forgone opportunities that a prioritization of investment inevitably includes. The most striking trade-off I found in the problem context of marine debris mitigation in the Asian seascape lay between the overall strategic aim of total debris removal by collecting large amounts of volume versus providing relief from downstream impacts for biodiversity and human populations. In this study, none of the selected options was the best option for all objectives, highlighting the importance of deliberating on the relative importance of different objectives and metrics. As long as decision-makers do not know exactly what they want to achieve, clean-up interventions will remain a somewhat random effort with uncertain benefits, particularly as the national or local waste management infrastructure into which the collected debris is entered after collection is likely to leak large volumes into the environment again, rendering the clean-up impact as only temporary relief. Political action, including regulation and reduction of plastic production, will likely play a more important role in the long term. However, the process of site selection is not only important in the context of marine debris but is also relevant in a range of other environmental decision contexts, from the placement of renewable energy infrastructure to waste disposal sites or conservation areas. Therefore, my contribution adds to the evidence that nuanced and rigorous deliberation on the underlying values that motivate action needs to be firmly anchored in the applied prioritization process. Of course, in addition to the necessary adjustments mentioned in the published paper, real-world implementation might want to consider some additional tweaks to the general method. Instead of just one most optimal project, costs will likely be used as a constraint to find the set of options that can deliver the best mix of benefits for a given budget. Real-world planning will likely require a longer process in which multiple stakeholders will have to meet repeatedly to adjust planning steps and agree on different details (Pierce et al. 2005; Theobald et al. 2000; Gregory et al. 2012; Knight et al. 2011). During that process, they will likely make use of weighting options for the relative importance of different objectives, which will likely change ranking during the shortlisting process. However, as outlined in the introduction, attention is needed when using relative weights to create meaningful differences (Game et al. 2013).

In conclusion, my PhD challenges the concept of peer-reviewed scientific literature as a high-quality source of information. Despite the existence of many high-quality papers in the scientific literature, my chapters highlight important weaknesses in several aspects of decision-making for conservation in science and practice. These weaknesses range from the production of data (chapter 4) to interpreting data (chapter 2), to the processes applied to assist in decision-making (chapter 3), to the framing and strategic thinking in conservation applications (chapter 5). The information that is used to inform decision-making efforts for conservation science and practice by identifying gaps and biases in geographic and taxonomic coverage of conservation management studies is just one example that shows how the lack of nuanced analysis can obfuscate important details, which could have vast implications and misspending of scarce resources. Knowing that, for example, other variables than taxonomy have larger gaps and biases or that certain areas of the world have fewer examples of vertebrates compared to other taxa is more informative for strategic conservation science and practice than an overall trend in grouped data. Once an important conservation problem is identified, and decision-makers have to decide which solution might deliver the best outcome, my thesis shows how important the choice of the employed decision-support framework can be. Because systematic reviews are one of the most fundamental building blocks for understanding broad patterns, the additional research into assessing the reliability of classified data from text has shown that common metrics are not able to detect the most common source of disagreement between raters, the humble mistake. My novel assessment method provides an alternative that not only detects variables with low agreement but also indicates underlying issues and the relative reliability of different raters.

My final chapter provides a clear example of how a well-applied decision-support framework can improve the strategic thinking for a well-known environmental problem and provides decision-makers with enough nuanced information to be able to identify solutions that deliver for those objectives that are most important in their socio-political context. All of my chapters provide insights into aspects of decision-making that are transferable to other scientific fields and describe clear pathways for improved decision-making for conservation science and practice.

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Appendix

Appendix I: Supplementary Materials for chapter 2

Supplementary material S2.1: summary of interrater reliability test

To establish clear categories, all categories were tested for general feasibility based on a set of 20 examples (4 drawn from each framework) by the lead author, and categories were edited to improve clarity and fit before coding the full set of 466 examples. Then 25 random examples were coded in parallel by 4 additional raters, and differences in classification were discussed in a group discussion. These discussions aimed to separate misclassifications from true disagreements, assuming that true disagreements stem from either different views or interpretation whenever there was ambiguity within the text. Three raters were in the mid or end phase of their Bachelor degree, and one rater was in in the final stages of his Master degree. Available funds (~AUD 10.000) were used as a primary stopping rule and all raters were paid for individual coding and discussions with a standard hourly rate until the money was used up. The moderate sample size of 25 papers is justified as a reasonable sample in light of budget and time constraints (Simmons et al. 2011).

A first test was based on the first 20 papers in the database, and categories were reworked in form of adding or collapsing classification options where necessary. In a next step, a parallel coding session with five additional raters and five papers was done, followed by a group discussion to identify unclear categories and classifications, and add or collapse options where necessary. Raters were reminded repeatedly that the purpose of the group discussion was not to reach agreement, but to share evidence and distinguish mistakes from true disagreements. The pilot of parallel coding with five raters was at the same time considered as a training session. The coding was repeated with the updated criteria to make sure no questions remained. After this test, the set of categories and classifications was considered to be robust, and the rest of the 466 examples were rated by the main author. The reliability of the extracted information was consecutively assessed through a further inter-rater-reliability test with four of the trained raters and 21 examples from each framework. The examples were partly targeted to include highly cited papers, and partly randomised. As in the pilot, parallel individual rating was followed by a group discussion and option to revise entries. Percent agreement (Feng 2014) of over 80% was reached for all categories when comparing the authors entries from initial and corrected ratings after group discussion (Garrison et al. 2006; Campbell et al. 2013).

Supplementary material S2.2: Cheat sheet: definition of categories to extract

Short concept:

When conservation actions get planned, different types of information and data are used, often within a strategic conceptual planning process. This cheat sheet defines different types of information that are in general important during decision-making and gives options for classifications within the coding table, to be used in the data entry form in the MS-ACCESS-database.

Most important:

1) You only want to extract information that was important during the planning for a distinct case study!

Only information that was directly and explicitly used in some way to come to a decision (for example as a parameter or input in a model) should get noted. The focus hereby lies on the conservation asset (the thing we care about), and the actions that should be taken for its benefit.

If for example a threat or an objective is in general mentioned as important, or stated that it was used, but is then not part of the description, (= not included in the modeling/decision making process), then it does not count and should not appear in the field. Please note in the comment box if you come across a paper where the authors are not following up with details on their initial statements.

2) Please do not interpret

Only extract what is explicitly stated. Of course many plans could be used in other context, and you will have many associations come up in your mind when you read a text, but please do only fill in what is explicitly stated in the text for the described case-study.

<u>Technical notes:</u>

MS ACCESS does not perform well with shortcuts (control z/ control/y), please do not use any to avoid frustration. Email me if anything does not work as intended!

Reading vs. skimming: Due to the large amount of literature, strategic reading is recommended: read abstract and method section in detail, use keyword search for all fields that are still empty afterwards. In the case of very long and unstructured papers, skim the whole paper to find the relevant section, which can then be read in detail. Appropriate keyword search terms are suggested in the cheat sheet.

One entry in the database correlates to one decision: If a publication described several examples or case-studies of a decision problem that were not used within a scenario analysis for the same decision, the record has to be duplicated in order to have one data entry per described examples, not one entry per publication. Enter in comment-box, for example: *decision example 2 of 3 within paper xy.* Use the little arrows at the bottom right of the entry form to create a new entry at the end of the table, and do not forget to enter author and title as well for each new entry.

Field name	Categories	Definition	Example/potential difficulty	Example entry & keyword search if applicable
impl_sugg_sci	impl = implemented	Explicitly stated that this was implemented or is about to get implemented When a case study has been done: if this was tested in small scale and is now recommended to be done at a large scale, this would still count as *scientific applied* if done without any collaboration with people who would be able to implement it, and *suggested* if collaboration existed. *Implementation* means that it is rolled out over the whole area/population of interest	Skim abstract, intro and discussion for any mentioning of collaboration or implementation, check authorlist for departments or institutes outside of academia as a hint, although that is not enough on its own to justify and entry as "impl"	impl use keyword search: "implement "
	sugg = suggested trial	= tested/experiment at small scale or calculated **in collaboration** with people who have power to make decision about implementation (but more than just a co-author in the department!)		sugg
	scia = scientific applied	= experiment at small scale **without** collaboration with people who have power to make decision		scia
	scit= scientific theoretical	= theoretical science / calculated **without** collaboration with people who have power to make decision		scit

Country		Fill in name		If more than one, separate by comma, alphabetically sorted Type "theoretical" if theoretical paper not set in a specific location
Continent	1 = Europe 2 = Americas (US, Canada, Middle and South) 3 = Africa and middle East 4 = Asia and Russia and India 5 = Australia/NZ 6 = other (e.g. Pacific Islands, poles, High seas etc)			If country lies somewhere between and you are not sure, use both numbers and state uncertainty in text field (region)
Type management (focus on the asset we want to benefit)	0 = not mentioned 1 = spatial prioritization 2 = population management 3 = threat abatement 4 = restoration 5 = other	0 = not mentioned 1 = spatial prioritization for protection/action (where to do something, or where to have borders of park) 2 = population management (provide positive impact from inside of species of concern, e.g. increase numbers/survival, including management of harvest of species) 3 = threat abatement (reduce negative impact from human activity/other species outside of species of concern) 4 = restoration (focus on habitat/land management, not single species)	**Spatial prioritization PA:** - establishing a PA at priority sites **Species management:** - harvest management of wild mushrooms, - culling buffalo to keep population size within park carrying capacity, - controlling fishing effort - manual pollination of trees, - artificial nesting boxes, - clutch manipulation, - supplementary feeding, - disease/parasite management -species reintroduction - ex situ conservation - captive breeding, - artificial propagation, - gene banking **Threat abatement:** any type of site/area management like - putting up fences, - control of poachers - invasive/problematic species control - cutting vines off trees,	Choose all that apply, separate by comma, start with smallest number Describe in text field to the right: 1 = xxx, 3 = xxx…

		5 = other (e.g. education, awareness, legislation)	- preventing pollution - preventing unintentional killing like roadkill **Restoration:** habitat and natural process restoration like - creating forest corridors, - prairie re-creation, - riparian tree plantings, - coral reef restoration, - proscribed burns, - dam removal, fish ladders	
Threat	0 = not mentioned, 1 = residential/commercial development, 2 = agriculture/aquaculture, 3 = energy production/mining, 4 = transportation/service corridors, 5 = biological and resource use, 6 = human intrusion disturbance, 7 = natural system modification, 8 = invasive/other problematic species, 9 = pollution, 10 = other 11 = climate change	*Requirement: Direct threat that impacts biodiversity of concern (asset in species/ecosystem field) and gets addressed by action* **Do not include** - other processes that might have enabled this direct threat: most threats have humans as an underlying cause, but we are only interested in the immediate agent that is targeted by a proposed action (even though cats have been introduced by humans, they are recorded as 8) - threats that are listed as important, but are not addressed by any of the actions they plan.	**Difficulty:** **5 & 7:** It might be difficult to distinguish between biological and resource use and natural systems modification, for example when water is used for irrigation, as this often also leads to a change of a larger natural system through changed flow. If not sure, use both numbers, separated with a comma, and indicate in text field. Examples of modified systems are fire suppression, dams, abandonment of formerly managed areas, thinning, beach construction **6:** human intrusion means when a person shows up at a location and causes a problem (like trampling or scaring animals). General estimates of population density usually refer to 1 (unless stated that used as proxy for visitor at a place)	Choose all that apply, separate by comma, start with smallest number Describe in text field to the right: 1 = xxx, 3 = xxx…
Species system	0 = not mentioned explicitly (not sure if species, habitat, or other)	*This is ONLY about the natural asset that is supposed to benefit*	If individual species/ecosystems are described, name	Choose all that apply, separate by comma,

	1 = birds 2 = mammals 3 = other fauna taxa 4 = fish 5 = unspecific fauna species 6 = one or more individual tree species 7 = one or more non-tree individual plant species 8 = forest 9 = grass/shrub-land 10 = coral 11 = other (for example geomorphic features, rock/sand, processes) 12 = unspecific flora species 13 = broad ecotypes or habitat 14 = unspecified species (unclear if flora or fauna)	*from the actions, not species that act as threat!* The category should capture two things: 1) the specificity of the taxonomic level of species 2) differentiate between species level planning vs. habitat/ecosystem focused planning	them all, and add description to enable counting of species later. Do that also when there are very many and it seems tedious (as long as they are used in the objectives)	start with smallest number Describe in text field to the right: 1 = xxx, 3 = xxx...
Terr_mar_fresh	0 = not mentioned t = terrestrial m = marine f = freshwater	*rule: whatever terrain is providing the most space for the species. E.g. mangrove are terrestrial as most of the trees are outside of the water*	intertidal is t,m	Choose all that apply, separate by comma, order t,m,f Describe why you made the choice

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Supplementary material S2.3: different threats, management types and taxa across individual countries:

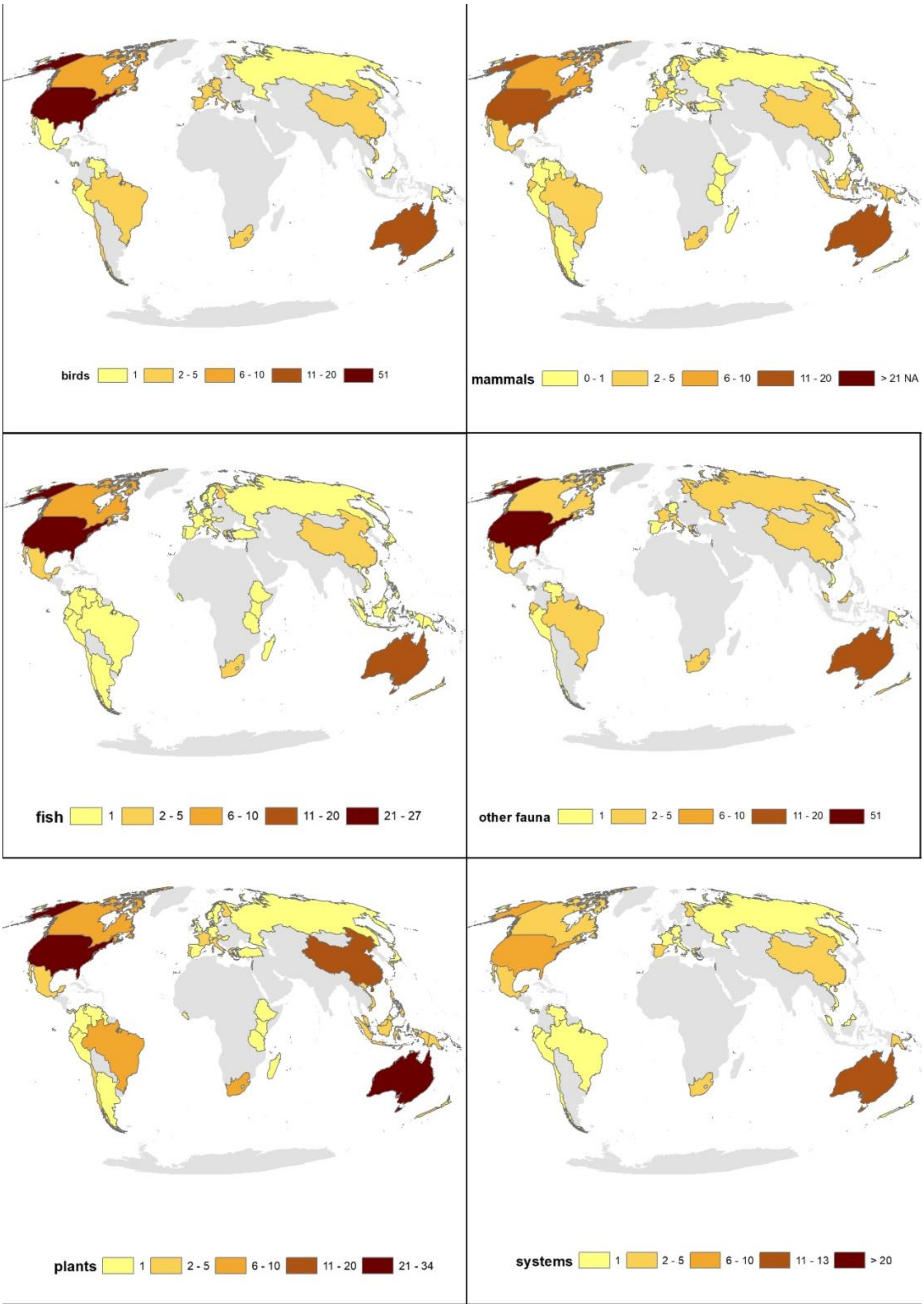

Figure S1. 1: a) Number of examples of taxonomic groups in described conservation decisions in individual countries. Countries for which no examples were found are greyed out.

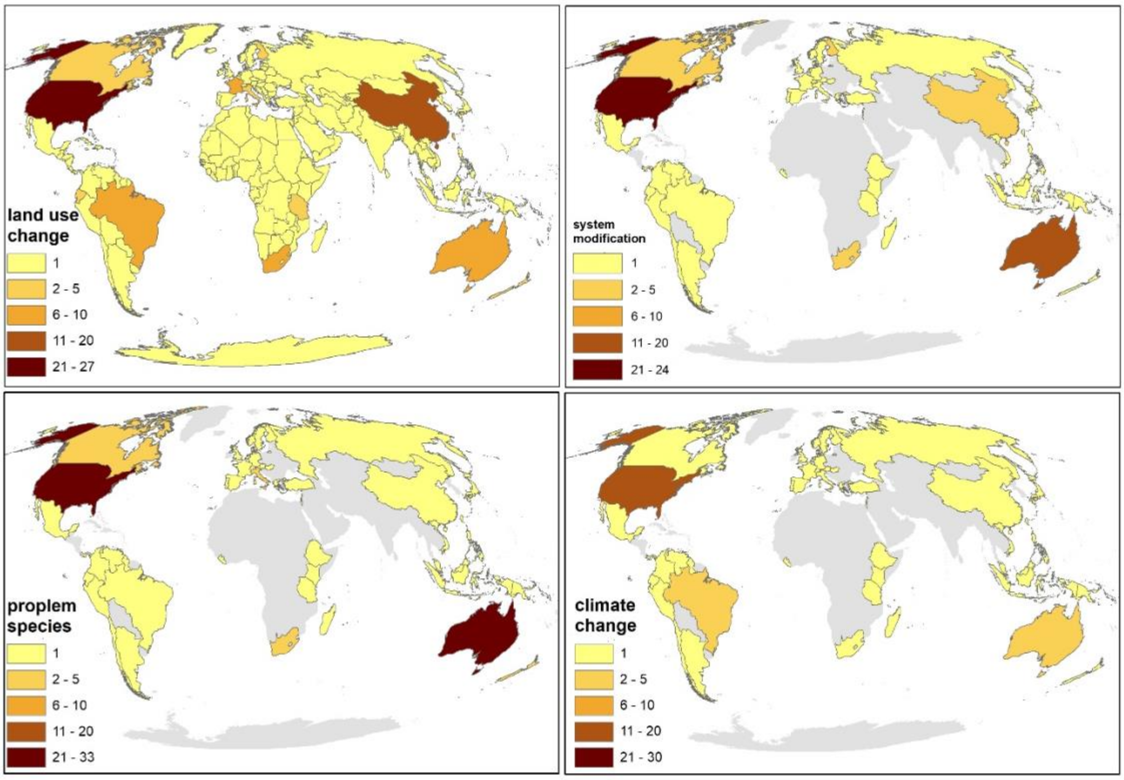

Figure S1. 2: b) Number of examples of threat groups in described conservation decisions in individual countries. Countries for which no examples were found are greyed out.

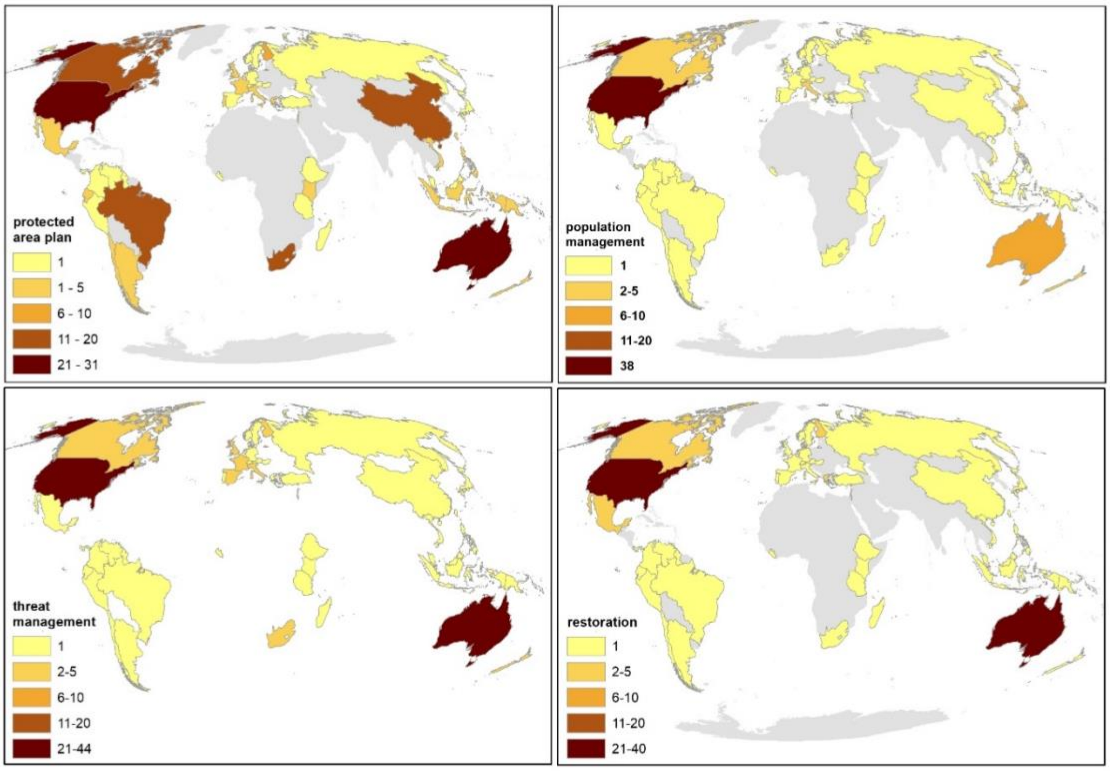

Figure S1. 3: c) Number of examples of management groups in described conservation decisions in individual countries. Countries for which no examples were found are greyed out.

Appendix II: Supplementary Materials for chapter 3

Supplementary material S3.1: key elements of decision-making

Clear objectives

Setting a clear objective sets the course of the decision-making process and is crucial to any conservation management plan (Possingham et al. 2001). The lack of clearly defined objectives is considered one of the most common mistakes in decision-making (Keeney 2002; Game et al. 2013). Clear objectives should be expressed in a quantitative way through appropriate metrics (Nicholson and Possingham 2006). Metrics that are appropriate indicators should be measurable, precise, consistent, and sensitive and need to be linked to the chosen objectives (Conservation Measures Partnership 2020).

Linking action and threat in a theory of change

A clear theory of change should be at the core of any decision on interventions in ecological systems. Decision-makers must be able to justify, through assumptions of cause and effect, how they expect their chosen action to create the expected benefit. A general correlation between conservation spending and the number of threatened mammals has been interpreted as proof that investment into conservation actions generally works (Waldron et al. 2017; Geldmann et al. 2018; Wintle et al. 2019). But more detailed assessments of the success rates of specific management strategies highlight the importance of spatial grain of the analysis. Of particular importance is linking actions to specific local threats: For example, marine restoration projects for different ecosystems show median survival rates of 50%

after 1-2 years, independent of the magnitude of investments. But instead of correlating with the size of investments, positive outcomes rather depend on site selection, ecotypes and field methods that consider existing threats like pollution and strong currents that impact survival (Bayraktarov et al. 2016). When specific threats are not mitigated under a management regime, deteriorating conditions can persist. Such examples include some particularly rapid declines in the last wilderness areas (Watson et al. 2016) and protected areas (Jantke et al. 2018; Jones et al. 2018). Although the main concept of establishing protected areas is the protection of habitat from land conversion, there is a general bias in the location of protected areas towards sites that do not face this particular threat (Joppa and Pfaff 2009). These examples highlight the importance of including explicit assumptions about the link between threats and actions in planning documents to enable not only meaningful outcomes but also evaluations of success and failure (Pressey et al. 2017). Because threats get often neglected in conservation planning, despite being a crucial part of any theory of change, we judged a clear link between action and threat as evidence that a theory of change had been established.

Socio-economic constraints

The inclusion of socio-economic constraints is critical when aiming to develop socially acceptable and scientifically defensible conservation plans (Ban and Klein 2009; Bodin et al. 2014; Whitehead et al. 2014). Conservation management often has to deal with limited funding, which makes the integration of likely costs crucial for efficiency. Additional socio-economic objectives are often the underlying cause for existing threats to biodiversity, and without their explicit integration, conservation projects might not gain public and political support. Because conservation management is likely to impact different groups of society, handling constraints such as opportunity or management cost as well as support from key stakeholders can determine the likelihood of successful implementation (Symes et al. 2016).

Sensitivity analysis

The importance of uncertainty in conservation management has been well established, including methods to address it in various forms (Regan et al. 2002). Despite evidence that addressing uncertainty can change prioritization of options in unexpected ways (Cabral et al. 2017), reviews of Systematic Conservation Planning and Multi-Criteria-Decision-Analysis have found that sensitivity analysis is often neglected (Delgado and Sendra 2004; Barr and Possingham 2013; Kullberg and Moilanen 2014; McIntosh et al. 2017; 2018; Adem Esmail and Geneletti 2018).

Deliberation on trade-offs

Apart from the need to address uncertainty around any data or models when aiming for a robust choice (Visconti and Joppa 2015), additional scrutiny and deliberation are required as soon as trade-offs have to be made. Trade-offs can become inevitable when planning for multiple objectives (Keeney 2002). If they are not addressed in a deliberate and transparent way, these trade-offs will be made implicitly based on sometimes vague or unconscious value-judgments (Game et al. 2013).

Supplementary material S3.2: keywords for the Web of Science search

The first stage used [[“decision-making” OR “decision making”] AND [“conserv*” OR “enviro*” OR “biodiv*” OR “ecolog*”]] to search literature on decisions with an environmental background, and a second step filtered for specific decision-aiding frameworks:

1 [“Structured Decision Making”]

2 [“Systematic Conservation Planning”]

3 [“Multi-criteria Decision Analysis” OR “Multi Criteria Decision Analysis” OR “MCDA”]

4 [“Adaptive Management”}

5 [“Cost-effective* prioritization” OR “cost effective* prioritization” OR “cost-effective* prioritisation” OR “cost effective* prioritisation” OR “cost-effective* analysis”]

(6 [“Strategic Foresight”] - disregarded)

(7 [“Horizon Scanning”] - disregarded)

Supplementary material S3.3: Cheat sheet: definition of categories to extract

<u>Short concept:</u>

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1) You only want to extract information that was important during the planning for a distinct case study!

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Table S2. 1: Complete Cheat Sheet with all variables and categories

Field name (and chapter in which it was used)	Categories	Definition	Example/potential difficulty	Example entry & keyword search
Type of decision (for consistency check with fields "count objectives" and "count actions"	Single objective, single action Multi objective, single action Single objective, multi action Multi objective, multi action Other reason included	*What is considered in a decision and compared/chosen between or traded off against each other?* **Definition of objective:** Objective that is clearly stated in text and describes what the goal of the management is, including a description of how this is tracked / linked to the decision of actions **Definition of action:** An action is an option to be evaluated through decision process and be decided between (should I do A or B?). Implementing a set of actions together to achieve a goal does not make it multi action if there is no selection process on which one to do. Only if there is a discrimination between options that have to be decided on makes a decision multi action.	**Objective:** Are multiple objectives given and tracked through the decision process? These can be targets for different species, or other aspects like costs or ecosystem services etc. which will appear for example in a ranking of options that shows clearly how well which option achieves which objective **Action:** is there a decision process to compare/decide between options, like building a fence to keep predator out OR baiting to kill a predator. Options can be very similar like building 1 fence or 2 fences, or killing 10% of weed or 40%, or building the fence at location A or B. **Difficulty:** If several scenarios are done that have different objectives and/or actions, please use the overall sum	Tickbox
impl_sugg_sci (used in chapter 2,3,4)	impl = Implemented	Explicitly stated that this was implemented or is about to get implemented When a case study has been done: if this was tested in small scale and is now recommended to be done at a large scale, this would still count as *scientific applied* if done without any collaboration with people who would be able to implement it, and *suggested* if collaboration existed. *Implementation* means that it is rolled out over the whole area/population of interest	Skim abstract, intro and discussion for any mentioning of collaboration or implementation, check authorlist for departments or institutes outside of academia as a hint, although that is not enough on its own to justify and entry as "impl"	impl use keyword search: "implement"

	sugg = Suggested trial	= tested/experiment at small scale or calculated **in collaboration** with people who have power to make decision about implementation (but more than just a co-author in the department!)		sugg
	scia = scientific applied	= experiment at small scale **without** collaboration with people who have power to make decision		scia
	scit= scientific theoretical	= theoretical science / calculated **without** collaboration with people who have power to make decision		scit
primary framework (used in chapter 3,4)	SDM = structured decision making SCP = Systematic conservation planning AM = Adaptive management MCDA = Multi-criteria decision analysis CE = Cost-effectiveness analysis	All of these that were explicitly stated to have been used, divided by comma, sorted alphabetically	Use search function to find and check if only mentioned in theory or explicitly stated that used **Difficulty:** Uncertainty what the different framework actually does – not important, just go with what they explicitly say they have used and copy paste that line/paragraph into description box.	AM, CE, MCDA, SCP, SDM
Country (used in chapter 2,3,4)		Fill in name		If more then one, separate by comma, alphabetically sorted Type "theoretical" if theoretical paper not set in a specific location
Continent Consistency check with field "country" (used in chapter 2,3,4)	1 = Europe 2 = Americas (US, Canada, Middle and South) 3 = Africa and middle East 4 = Asia and Russia and India 5 = Australia/NZ 6 = other (e.g. Pacific Islands, poles, High seas etc)			If country lies somewhere between and you are not sure, use both numbers and state uncertainty in text field (region)

Type management (focus on the asset we want to benefit) (used in chapter 2,3,4)	0 = not mentioned 1 = spatial prioritization 2 = population management 3 = threat abatement 4 = restoration 5 = other	0 = not mentioned 1 = spatial prioritization for protection/action (where to do something, or where to have borders of park) 2 = population management (provide positive impact from inside of species of concern, e.g. increase numbers/survival, including management of harvest of species) 3 = threat abatement (reduce negative impact from human activity/other species outside of species of concern) 4 = restoration (focus on habitat/land management, not single species) 5 = other (e.g. education, awareness, legislation)	**Spatial prioritization PA:** - establishing a PA at priority sites **Species management:** - harvest management of wild mushrooms, - culling buffalo to keep population size within park carrying capacity, - controlling fishing effort - manual pollination of trees, - artificial nesting boxes, - clutch manipulation, - supplementary feeding, - disease/parasite management -species reintroduction - ex situ conservation - captive breeding, - artificial propagation, - gene banking **Threat abatement:** any type of site/area management like - putting up fences, - control of poachers - invasive/problematic species control - cutting vines off trees, - preventing pollution - preventing unintentional killing like roadkill **Restoration:** habitat and natural process restoration like - creating forest corridors, - prairie re-creation, - riparian tree plantings, - coral reef restoration, - proscribed burns, - dam removal, fish ladders	Choose all that apply, separate by comma, start with smallest number Describe in text field to the right: 1 = xxx, 3 = xxx…
Socio economic objectives (used in chapter 3,4)	y/n	To choose from opportunity cost, management cost, recreation, ecosystem services, support, or other		

Type **environmental, economic, social and other** objectives (4 separate fields with the same categories, 1-4 were counted as quantitative) (used in chapter 3,4)	0 = not clearly stated 1 = maximise *(mathematical formula)* 2 = minimise *(mathematical formula)* 3 = depends on combination with other objective 4 = target/threshold 5 = other 6 = increase	*Environmental objective means here: objective for a natural asset (something that is supposed to benefit from action).* Objective for threats-only actions are NOT of interest here! If an action is only targeting a threat without linking it explicitly to a natural asset that should benefit, the environmental objectives field stays empty (0) **Minimisation and maximisation** are mathematical optimisation procedures that require a technical formula. If people just try to somehow increase presence/numbers but measure that not via a rigorous mathematical procedure, classify as 6	Example for 3: area per dollar spent: this is neither maximizing area nor minimizing cost, but the best option depends on the combination Example for 5: vague description like increase or benefit without further specification	Choose all that apply, separate by comma, start with smallest number Separate lines for, economic, social and environmental objective Describe in text field to the right: 1 = xxx, 3 = xxx… Keyword*: "max", "min", "target", "thresh", increase"*
Count objectives (used in chapter 4)	1 = 1 2 = 2 3 = 3 or 4 5 = 5 or more	*How many objectives are explicitly stated?* *That should relate to checkboxes upper left corner, and to the more detailed boxes on objective types on the lower left side*		Keyword: *"objective"*
alternative actions count (used in chapter 4)	1 = 1 2 = 2 3 = 3 or 4 5 = 5 or more	*That should relate to checkboxes upper left corner* Count of options **that are compared to each other as options of choice**: can be single actions, or set of actions that are planned to get implemented together.	A "do nothing" option counts as option, and a decision between doing one action or not doing it is classified as 2. Only papers that plan for one action that do not compare this to a do-nothing-option get classified as 1.	Describe in text field to the right: 1 = xxx, 2 = xxx…, 3 = xxx, 5=xxx

Explicit trade-off attempted between options (used in chapter 3,4)	Yes/no	*A trade-off is an explicit comparison that attempts to balance between (potentially opposing) objectives: you can't have it all, but you try to find out what option gets you the best mix of all the things you care for. Often different objectives or different opinions have to be combined to come to a conclusion during a tradeoff, which is addressed by information entered in fields below (tradeoff aggregation type and type ranking)*		Search keyword: *tradeoff, trade-off*
Sensitivity or scenario analysis type *What is done to test if the result might be different under other circumstances? What is changed in the calculation to test this?* Any entry was counted as "yes" (used in chapter 3,4)	0= no scenario or sensitivity analysis mentioned 1 = epistemic uncertainty /measured parameter values changed within model/calculation 2 = different models used 3 = weights changed within model/calculation 4 = scores changed within model/calculation 5 = scenarios for different actions (but same calculation) → (likely if you checked multi action) 6 = objective set (but same calculation) 7 = other 8 = spatial inclusions/exclusion (but same calculation) 9 = scenarios for different targets (but same calculation)	*The definitions of "scenario analysis" and "sensitivity analysis" are not crystal clear and somewhat overlap. Most important: they describe an attempt of finding out if the result would be different, if you make slight changes during the procedure. This field should contain a description of what has been tested if it results in a change.*	Epistemic uncertainty is uncertainty that results from natural variation: for example testing a model for different age, size or survival of an animal. A different model would mean that for example 2 different softwares, or a math model and expert elicitation have been compared	Choose all that apply, separate by comma, start with smallest number Describe in text field to the right: 1 = xxx, 3 = xxx… Keyword: "*sensi*", "*scenario*"

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Supplementary material S3.4: Reliability testing:

To establish clear categories, all categories were tested for general feasibility based on a set of 20 examples (4 drawn from each framework) by the lead author, and categories were edited to improve clarity and fit before coding the full set of 466 examples. Then 25 random examples were coded in parallel by 4 additional raters, and differences in classification were discussed in a group discussion. These discussions aimed to separate misclassifications from true disagreements, assuming that true disagreements stem from either different views or interpretation whenever there was ambiguity within the text. Three raters were in the mid or end phase of their Bachelor degree, and one rater was in in the final stages of his Master degree. Available funds (~AUD 10.000) were used as a primary stopping rule and all raters were paid for individual coding and discussions with a standard hourly rate until the money was used up. The moderate sample size of 25 papers is justified as a reasonable sample in light of budget and time constraints (Simmons et al. 2011).

A first test was based on the first 20 papers in the database, and categories were reworked in form of adding or collapsing classification options where necessary. In a next step, a parallel coding session with five additional raters and five papers was done, followed by a group discussion to identify unclear categories and classifications, and add or collapse options where necessary. Raters were reminded repeatedly that the purpose of the group discussion was not to reach agreement, but to share evidence and distinguish mistakes from true disagreements. The pilot of parallel coding with five raters was at the same time considered as a training session. The coding was repeated with the updated criteria to make sure no questions remained. After this test, the set of categories and classifications was considered to be robust, and the rest of the 466 examples were rated by the main author. The reliability of the extracted information was consecutively assessed through a further inter-rater-reliability test with four of the trained raters and 21 examples from each framework. The examples were partly targeted to include highly cited papers, and partly randomised. As in the pilot, parallel individual rating was followed by a group discussion and option to revise entries. Percent agreement (Feng 2014) of over 80% (Figure S2. 1) was reached for all categories when comparing the authors entries from initial and corrected ratings after group discussion (Garrison et al. 2006; Campbell et al. 2013). The details of the inter-rater-reliability will be published independently (Beher et al in prep, Chapter 4 of this thesis).

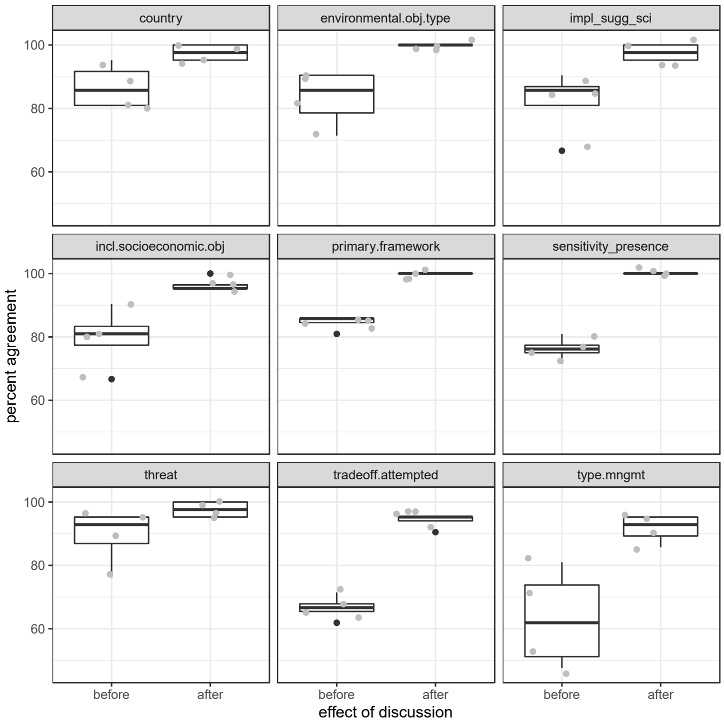

Figure S2. 1: percent agreement before and after discussion between the average of 4 pair-wise comparison between the raters and the first author for 25 decision examples and 9 coded categories.

Supplementary material S3.5: Scanning

Table S2. 2: Count of papers in different filtering stages in the search for described decisions processes for conservation management that use one of the frequently used decision support frameworks. 110 Horizon scanning and 94 Strategic Foresight papers were sighted but did not contain relevant information for current biodiversity conservation planning and were therefore excluded for the subsequent analysis.

Framework →	**Structured Decision making**	**Systematic Conservation Planning**	**Multi Criteria Decision Analysis**	**Cost - Effectiveness Prioritization**	**Adaptive management**	**Total**
Total number of results in Web of Science core collection →	292	476	1708	1517	3113	7106
Remaining after checking title/journal of 7310 publications→	149	411	1105	246	2689	4600
Remaining after checking abstract of 4701 publications from 2009-2019 →	98	342	110	64	533	1147
Remaining after reading 1218 publications from 2009-2019 →	49	212	40	29	157	487
Remaining after correcting mismatches between search-term and actual framework used, and removing redundancy. Number without brackets: One framework only, number in brackets: combination with one or more of 4 other frameworks	27 (59)	212 (225)	40 (49)	34 (53)	106 (145)	424 (531) **Total examples: 466**

Supplementary material S3.6: Use of elements over time

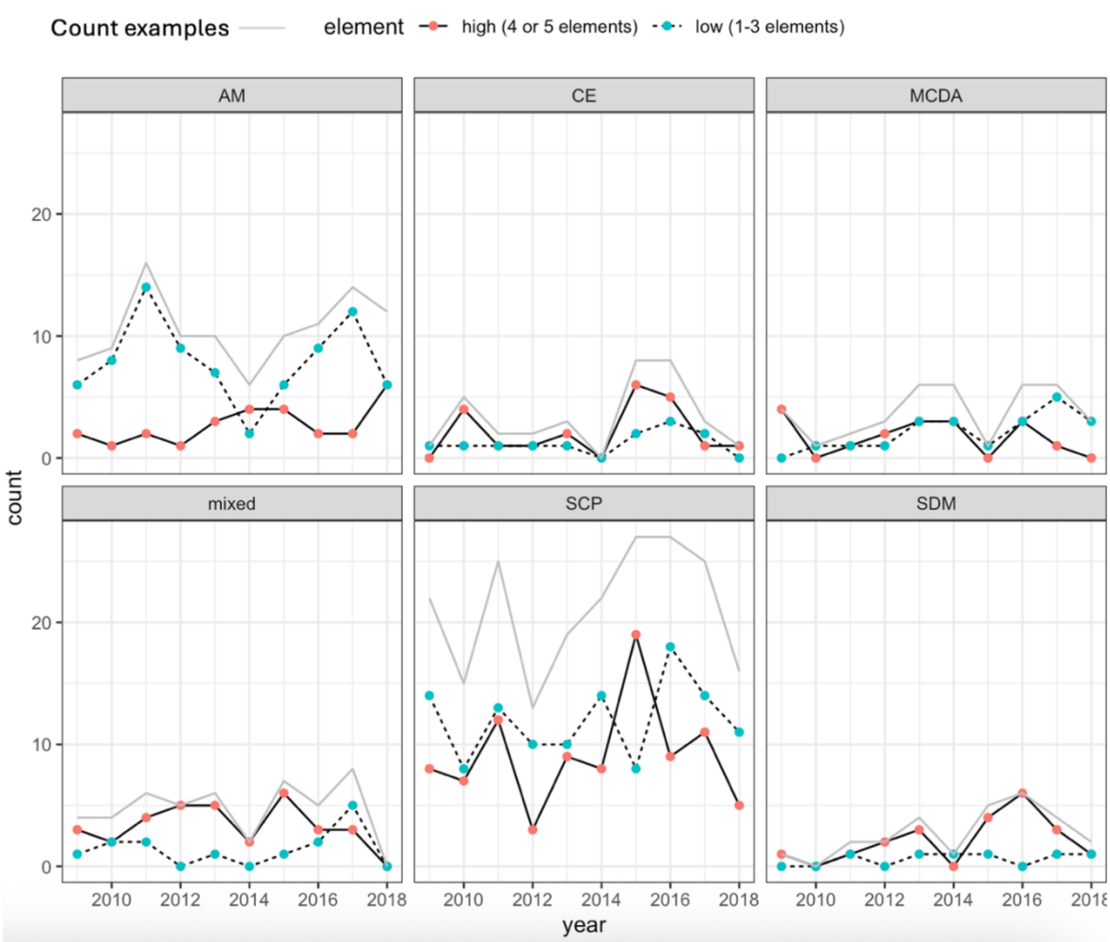

Figure S2. 2: There is no clear trend of an increase over time in any of the frameworks, and no trend of using a higher (4-5) or lower (1-3) number of elements over time for any of the decision-support options.

Supplementary material S3.7: Co-author network:

To rule out that best practice decision-making is driven by specific authors that publish a lot, an analysis of co-authorship of best practice examples was done. The result (Figure S2. 3) shows a large number of individual examples as components in the network that have no connection to other examples, which means that everyone in the group of co-authors has only published this one best-practice example. The main exception is one large component with multiple connections between authors of different examples, which includes many researchers from the Centre of Excellence of Environmental Decisions in Australia. The high number of authors that have only published one best practice example, particularly under Structured Decision Making, does not support the assumption that individual prolific authors are driving good practice. For Systematic Conservation Planning and Cost Effectiveness as well as for authors that published papers with different individual frameworks, the Centre of Excellence of Environmental Decision Making seems to have a substantial influence in academic context.

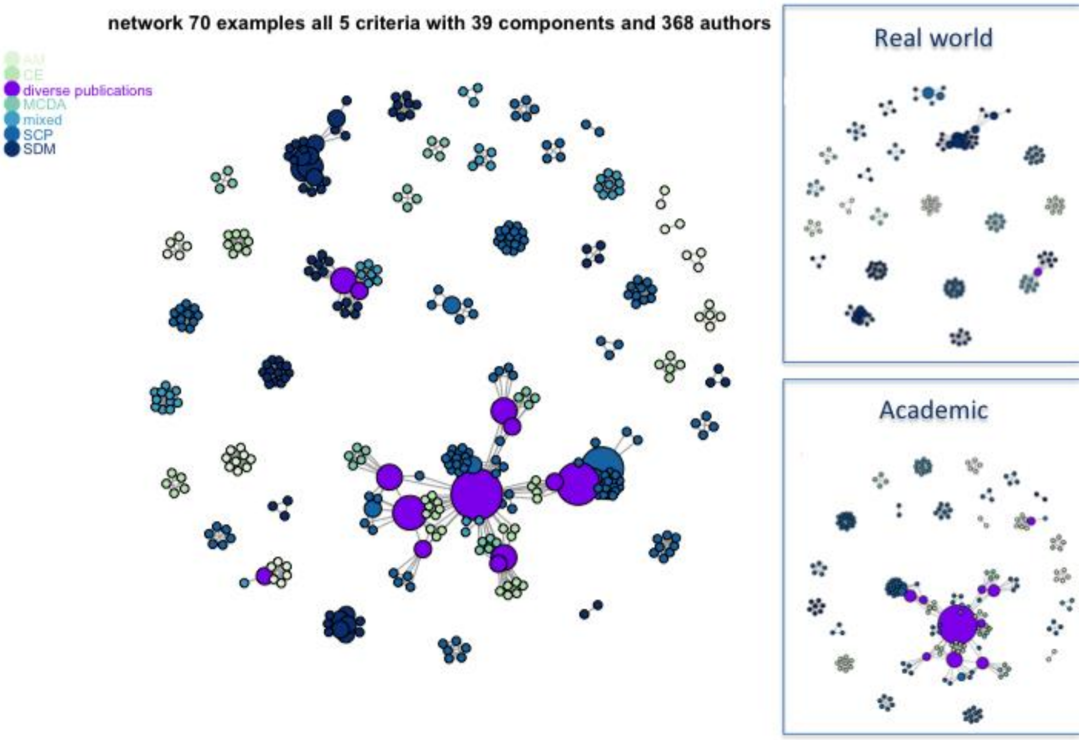

Figure S2. 3: A network map of co-authorship shows one large component of connected authors of multiple publications, few smaller components and mostly individual publications (~30 out of 70). Each circle (node) represents an individual author, and each line (edge) a link to a co-author. A purple node indicates that the author has published papers that use different framework. The size of each node is proportional to the number of papers of each author. The large node in the center of the large component is Hugh Possingham (co-author on 10 out of 70 examples = 15%), and the component consists mainly of academic work (see split up networks for academic and conservation practice examples on the right).

Supplementary material S3.8: Spatial bias of management examples

Countries without examples match known biases due to lack of data and language barriers. Best practice examples exist on all continents for ~20 countries, with the same bias towards Australia and US, which provide over half of the best practice examples (40 out of 70). Conservation practice examples in general and those including more than 3 key decision elements have been found for fewer countries than academic examples. Particularly Europe, Latin America, China and Indonesia seem to be more commonly represented in form of academic planning exercises than in applied context.

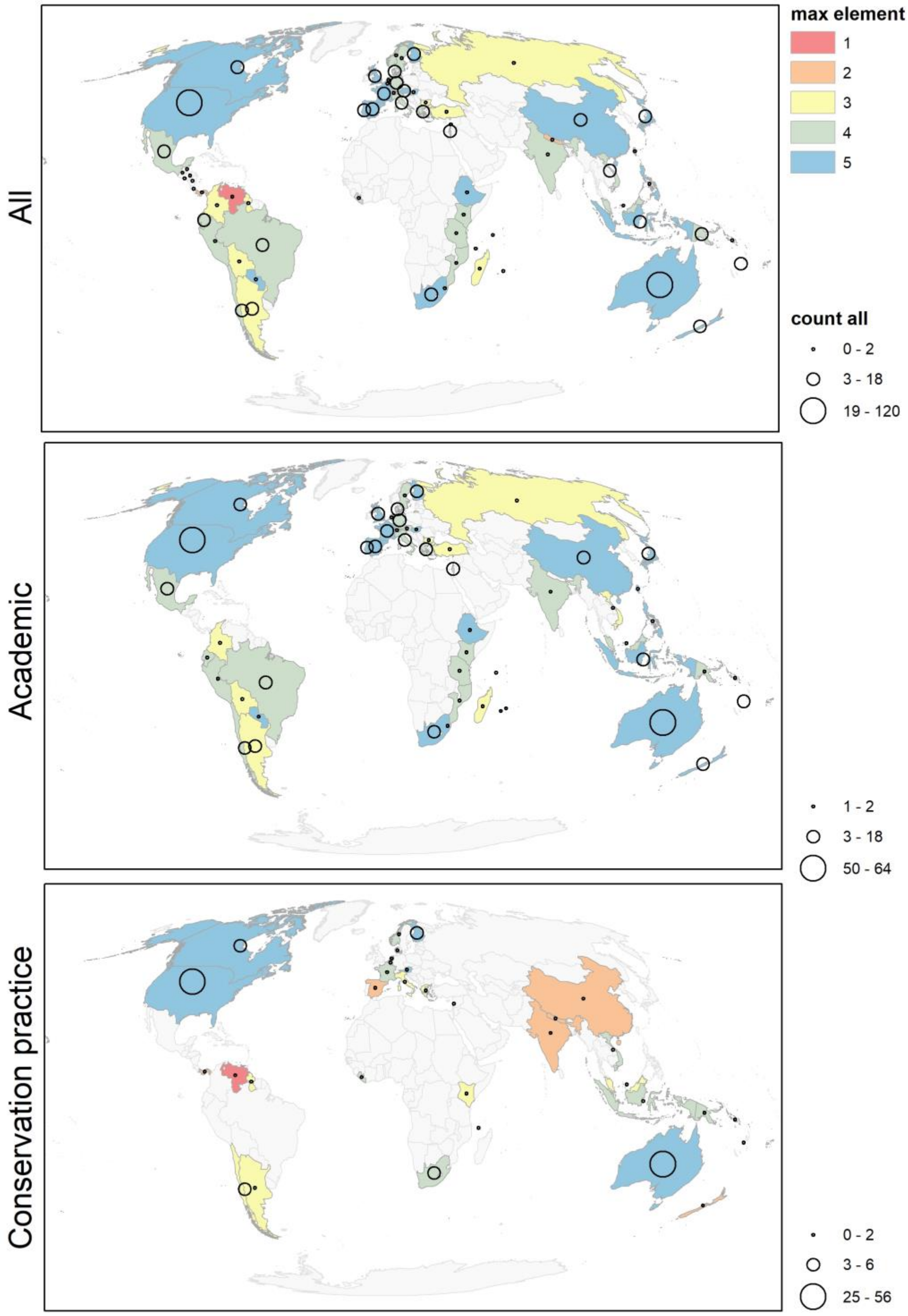

Figure S2. 4: Location of conservation management planning around the globe: Examples of decision-making can be found for many countries around the world (top panel), but numbers are biased towards the US (120 examples) and Australia (75 examples) while only one or two examples were found for most other countries. For many countries only academic examples were found, and the dominance of the US and Australia in numbers of general and best practice examples is most obvious in conservation practice contexts. Note that the legend for counts gives the highest and lowest number for each panel within three bins (1-2, 3-19, 20 -120).

Supplementary material S3.9: Data table with all papers and categories

Table S2. 3: Titles, variables and categories of examples analysed in chapter 3

Title	Author	Frame-work	Implementation	Country	Management Type	Quantitative Objective	Threat Link	Socio-economic Objective	Sensi-trinity analysis	Trade-off
3D spatial conservation prioritisation: Accounting	Venegas-Li, R; Levin, N; Possingham, H; Kark, S"	SCP	academic	Mediterranean Sea	Spatial Prioritisation	1	1	1	1	1
A Bayesian Belief Network Decision Support Tool for Watering Wetlands to Maximise Native Fish Outcomes	Gawne, B; Price, A; Koehn, JD; King, AJ; Nielsen, DL; Meredith, S; Beesley, L; Vilizzi, L	AM	conservation practice	Australia	Mixed Management	1	1	0	1	0
A comparison of approaches used for economic analysis in marine protected area network planning in California	White, JW; Scholz, AJ; Rassweiler, A; Steinback, C; Botsford, LW; Kruse, S; Costello, C; Mitarai, S; Siegel, DA; Drake, PT; Edwards, CA	SCP	conservation practice	US	Spatial Prioritisation	1	1	1	1	1
A conservation assessment of Canada's boreal fores	Powers, RP; Coops, NC; Tulloch, VJ; Gergel, SE; N	SCP	academic	Canada	Spatial Prioritisation	1	0	1	1	1
A conservation planning approach to mitigate the i	Bode, M; Tulloch, AIT; Mills, M; Venter, O; Ando,	SCP	academic	NA	Mixed Management	1	1	1	1	1
A decision framework for management of conflicting production and biodiversity goals for a commercially valuable invasive species	Grechi, I; Chades, I; Buckley, YM; Friedel, MH; Grice, AC; Possingham, HP; van Klinken, RD; Martin, TG	MCDA	academic	Australia	Threat Abatement	1	1	1	1	1
A Decision Support Tool for Adaptive Management of Native Prairie Ecosystems	Hunt, VM; Jacobi, SK; Gannon, JJ; Zorn, JE; Moore, CT; Lonsdorf, EV	AM	conservation practice	US	Mixed Management	1	1	1	1	0
A decision-analytic approach to the optimal alloca	Converse, SJ; Shelley, KJ; Morey, S; Chan, J; LaTi	SDM	conservation practice	US	NA	1	0	1	1	0
A framework for deriving and triggering thresholds for management intervention in uncertain, varying and time-lagged systems	Scholes, RJ; Kruger, JM	AM	academic	South Africa	Threat Abatement	1	1	0	1	0
A framework for systematic conservation planning a	Levin, N; Watson, JEM; Joseph, LN; Grantham, HS;	SCP	academic	Israel	Mixed Management	1	0	1	1	1
A GIS-based decision-making approach for prioritizing seabird management	Borrelle, SB; Buxton, RT; Jones, HP; Towns, DR	MCDA	academic	New Zealand	Mixed Management	1	1	0	0	0

following predator eradication										
A Markov Decision Process for Managing Habitat for Florida Scrub-Jays	Johnson, FA; Breininger, DR; Duncan, BW; Nichols, JD; Runge, MC; Williams, BK	AM	conservation practice	US	Restoration	1	1	0	1	0
A Matter of Tradeoffs: Reintroduction as a Multipl	Converse, SJ; Moore, CT; Folk, MJ; Runge, MC	mixed	conservation practice	US	Population Management	1	0	1	1	1
A meta-decision-analysis approach to structure operational and legitimate environmental policies - With an application to wetland prioritization	Choulak, M; Marage, D; Gisbert, M; Paris, M; Meinard, Y	MCDA	academic	France	Spatial Prioritisation	0	0	1	1	0
A Multi-objective Optimization Approach Associated	Schlottfeldt, S; Timmis, J; Walter, ME; Carvalho,	SCP	academic	Brazil	Spatial Prioritisation	1	1	1	1	0
A Multi-objective, Return on Investment Analysis	Kramer, DB; Zhang, T; Cheruvelil, KS; Ligmann-Zie	CE	academic	US	Threat Abatement	1	1	1	1	1
A multidisciplinary approach in the design of mari	Ruiz-Frau, A; Possingham, HP; Edwards-Jones, G; K	SCP	academic	UK	Spatial Prioritisation	1	0	1	1	0
A participatory approach for selecting cost-effective measures in the WFD context: The Mar Menor (SE Spain)	Perni, A; Martinez-Paz, JM	mixed	academic	Spain	Threat Abatement	0	1	1	1	0
A proposed framework to systematically design and objectively evaluate non-dominated restoration tradeoffs for watershed planning and management	Martin, DM; Hermoso, V; Pantus, F; Olley, J; Linke, S; Poff, NL	MCDA	academic	Australia	Mixed Management	1	1	1	1	1
A regional-scale ecological risk framework for environmental flow evaluations	O'Brien, GC; Dickens, C; Hines, E; Wepener, V; Stassen, R; Quayle, L; Fouchy, K; MacKenzie, J; Graham, PM; Landis, WG	AM	conservation practice	South Africa	Mixed Management	0	1	1	1	1
A reliance on agricultural land values in conserva	Sutton, N; Cho, S; Armsworth, PR"	SCP	academic	US	Spatial Prioritisation	1	0	1	1	0
A scientific basis for restoring fish spawning habitat in the St. Clair and Detroit Rivers of the Laurentian Great Lakes	Manny, BA; Roseman, EF; Kennedy, G; Boase, JC; Craig, JM; Bennion, DH; Read, J; Vaccaro, L; Chiotti, J; Drouin, R; Ellison, R	AM	conservation practice	US	Restoration	1	1	1	1	0

A spatial multicriteria decision analysis for selecting priority sites for plant species restoration: a case study from the Chilean biodiversity hotspot	Fernandez, IC; Morales, NS	MCDA	academic	Chile	Mixed Management	0	0	1	0	0
A straightforward conceptual approach for evaluati	Loyola, RD; Lemes, P; Nabout, JC; Trindade, J; Sa	SCP	academic	Brazil	Spatial Prioritisation	1	1	1	1	0
A Strategy for Monitoring and Managing Declines in	Grant, EHC; Zipkin, EF; Nichols, JD; Campbell, JP	SDM	conservation practice	US	Mixed Management	1	1	1	0	1
A Strategy for Prioritizing Threats and Recovery Actions for At-Risk Species	Darst, CR; Murphy, PJ; Strout, NW; Campbell, SP; Field, KJ; Allison, L; Averill-Murray, RC	AM	academic	US	Mixed Management	1	1	0	1	0
A Structured Approach to Incidental Take Decision	McGowan, CP	SDM	academic	US	Population Management	1	1	0	1	1
A systematic approach for prioritizing multiple ma	Januchowski-Hartley, SR; Visconti, P; Pressey, RL	SCP	conservation practice	Australia	Mixed Management	1	1	1	1	1
A systematic approach towards the identification a	Ardron, JA; Clark, MR; Penney, AJ; Hourigan, TF;	mixed	academic	NA	Spatial Prioritisation	1	1	1	1	1
A systematic conservation planning approach to fir	Foresta, M; Carranza, ML; Garfi, V; Di Febbraro,	SCP	academic	Italy	Spatial Prioritisation	1	1	0	0	0
A SYSTEMATIC EVALUATION OF THE CONSERVATION PLANS	Lourival, R; McCallum, H; Grigg, G; Arcangelo, C;	SCP	academic	Brazil	Spatial Prioritisation	1	1	1	1	0
A systematic evaluation of the incremental protec	Beckley, LE; Lombard, AT"	SCP	academic	Australia	Spatial Prioritisation	1	1	1	0	0
A three-step approach to minimise the impact of a mining site on vicua (Vicugna vicugna) and to restore landscape connectivity	Mata, C; Malo, JE; Galaz, JL; Cadorzo, C; Lagunas, H	AM	conservation practice	Chile	Threat Abatement	1	1	0	1	0
A transdisciplinary approach to the economic analysis of the European Water Framework Directive	Martin-Ortega, J; Perni, A; Jackson-Blake, L; Balana, BB; Mckee, A; Dunn, S; Helliwell, R; Psaltopoulos, D; Skuras, D; Cooksley, S; Slee, B	CE	academic	UK	Mixed Management	0	1	1	1	0
Accounting for farmers' production responses to environmental restrictions within landscape planning	Ahrenz, H; Kantelhardt, J	MCDA	academic	Germany	NA	1	1	1	1	0

Acting Optimally for Biodiversity in a World Obses	Venter, O; Hovani, L; Bode, M; Possingham, HP"	SCP	academic	Indonesia	Mixed Management	1	1	1	1	0
Adapting environmental management to uncertain but inevitable change	Nicol, S; Fuller, RA; Iwamura, T; Chades, I	mixed	academic	Asia, Pacific	Spatial Prioritisation	1	1	1	1	0
Adapting to changing poaching intensity of yellow-shouldered parrot (Amazona barbadensis) nestlings in Margarita Island, Venezuela	Briceno-Linares, JM; Rodriguez, JP; Rodriguez-Clark, KM; Rojas-Suarez, F; Millan, PA; Vittori, EG; Carrasco-Munoz, M	AM	conservation practice	Venezuela	Mixed Management	0	1	0	0	0
Adaptive Comanagement of a Marine Protected Area Network in Fiji	Weeks, R; Jupiter, SD	mixed	conservation practice	Fiji	Spatial Prioritisation	1	1	1	1	0
Adaptive management for improving species conservation across the captive-wild spectrum	Canessa, S; Guillera-Arroita, G; Lahoz-Monfort, JJ; Southwell, DM; Armstrong, DP; Chades, I; Lacy, RC; Converse, SJ	AM	academic	US	Mixed Management	1	0	0	1	1
Adaptive management for improving species conservation across the captive-wild spectrum	Canessa, S; Guillera-Arroita, G; Lahoz-Monfort, JJ; Southwell, DM; Armstrong, DP; Chades, I; Lacy, RC; Converse, SJ	AM	academic	US	Population Management	1	0	0	0	1
Adaptive management for improving species conservation across the captive-wild spectrum	Canessa, S; Guillera-Arroita, G; Lahoz-Monfort, JJ; Southwell, DM; Armstrong, DP; Chades, I; Lacy, RC; Converse, SJ	AM	academic	US	Population Management	1	0	0	1	0
Adaptive management of an environmental watering event to enhance native fish spawning and recruitment	King, AJ; Ward, KA; O'Connor, P; Green, D; Tonkin, Z; Mahoney, J	AM	conservation practice	Australia	Restoration	0	1	1	1	0
Adaptive management of animal populations with significant unknowns and uncertainties: a case study	Gerber, BD; Kendall, WL	AM	conservation practice	US	Population Management	1	1	0	1	0
Adaptive Management of Bull Trout Populations in the Lemhi Basin	Tyre, AJ; Peterson, JT; Converse, SJ; Bogich, T; Miller, D; van der Burg, MP; Thomas, C; Thompson, R; Wood, J;	AM	conservation practice	US	Restoration	1	1	0	1	0

	Brewer, DC; Runge, MC									
Adaptive management of natural systems using fuzzy logic	Prato, T	AM	academic	theoretical	Threat Abatement	1	1	0	1	0
Adaptive management of sika deer populations in Hokkaido, Japan: theory and practice	Kaji, K; Saitoh, T; Uno, H; Matsuda, H; Yamamura, K	AM	academic	Japan	Population Management	1	1	1	1	0
Adaptive management of the brown bear population in Hokkaido, Japan	Ohta, U; Jusup, M; Mano, T; Tsuruga, H; Matsuda, H	AM	academic	Japan	Population Management	1	1	1	1	1
Adaptive management on the central Platte River - Science, engineering, and decision analysis to assist in the recovery of four species	Smith, CB	mixed	conservation practice	US	Mixed Management	1	1	0	1	0
ADAPTIVE MANAGEMENT, RESTORATION, AND MONITORING FOR PERFORMANCE BASED RESULTS IN THE FISH CREEK WATERSHED IN NORTHEASTERN INDIANA AND NORTHWESTERN OHIO, USA	Simon, TP; Altfater, D; Tosick, MJ; Smith, JR; Faatz, W; Draper, J; Warner, BA; Wodrich, C; Remek, A; Campbell-Allison, J; Sparks, DW; Clark, F	mixed	conservation practice	US	Restoration	0	1	1	0	0
Adaptive resource management and the value of information	Williams, BK; Eaton, MJ; Breininger, DR	AM	academic	US	Restoration	0	1	0	1	0
Adaptively Managing Wildlife for Climate Change: A Fuzzy Logic Approach	Prato, T	AM	academic	theoretical	Threat Abatement	1	1	0	1	0
Addressing longitudinal connectivity in the system	Hermoso, V; Linke, S; Prenda, J; Possingham, HP"	SCP	academic	Spain, Portugal	Spatial Prioritisation	1	1	1	1	1
Addressing Wild Turkey Population Declines Using S	Robinson, KF; Fuller, AK; Schiavone, MV; Swift, BL	SDM	conservation practice	US	Population Management	1	1	1	1	1
Allocating conservation resources between areas where persistence of a species is uncertain	McDonald-Madden, E; Chades, I; McCarthy, MA; Linkie, M; Possingham, HP	CE	academic	Indonesia	Population Management	1	1	1	1	1
Allocation of European wetland restoration options	Schleupner, C; Schneider, UA"	SCP	academic	Europe	Mixed Management	1	0	1	1	1

American mink control on inland rivers in southern England: An experimental test of a model strategy	Harrington, LA; Harrington, AL; Moorhouse, T; Gelling, M; Bonesi, L; Macdonald, DW	AM	academic	UK	Mixed Management	0	1	0	0	0
An Adaptive Decision Framework for the Conservation of a Threatened Plant	Moore, CT; Fonnesbeck, CJ; Shea, K; Lah, KJ; McKenzie, PM; Ball, LC; Runge, MC; Alexander, HM	AM	academic	US	Population Management	1	1	0	1	0
An Adaptive-Management Framework for Optimal Contr	Martin, J; Fackler, PL; Nichols, JD; Runge, MC; Mc	mixed	conservation practice	US	Threat Abatement	1	1	1	1	0
An approach to GIS-based multiple criteria decision analysis that integrates exploration and evaluation phases: Case study in a forest-dominated landscape	Greene, R; Luther, JE; Devillers, R; Eddy, B	MCDA	conservation practice	Canada	Mixed Management	0	1	1	1	0
An evaluation and comparison of conservation guidelines for an at-risk migratory songbird	McNeil, DJ; Aldinger, KR; Bakermans, MH; Lehman, JA; Tisdale, AC; Jones, JA; Wood, PB; Buehler, DA; Smalling, CG; Siefferman, L; Larkin, JL	AM	conservation practice	US	Restoration	1	1	0	1	0
An integrated risk-assessment framework for multiple threats to floodplain values in the Kakadu Region, Australia, under a changing climate	Bayliss, P; Finlayson, CM; Innes, J; Norman-Lopez, A; Bartolo, R; Harford, A; Pettit, NE; Humphrey, CL; van Dam, R; Dutra, LXC; Woodward, E; Ligtermoet, E; Steven, A; Chariton, A; Williams, DK	AM	academic	Australia	Threat Abatement	0	1	1	1	0
An iterative method for discovering feasible management interventions and targets conjointly using uncertainty visualizations	Fu, BH; Guillaume, JHA; Jakeman, AJ	AM	academic	Australia	Restoration	1	1	0	1	1
Application of Science-Based Restoration Planning to a Desert River System	Laub, BG; Jimenez, J; Budy, P	mixed	conservation practice	US	Mixed Management	1	1	1	1	0
Applying Ecologically Based Invasive-Plant Management	Sheley, R; James, J; Smith, B; Vasquez, E	AM	academic	US	Restoration	1	1	0	1	0

Applying systematic conservation planning principl	Ausseil, AGE; Chadderton, WL; Gerbeaux, P; Stephe	SCP	academic	New Zealand	Spatial Prioritisation	1	1	0	0	0
Applying systematic conservation planning to cons	Ma, L; Sun, GQ; Qu, Y; Li, JQ"	SCP	academic	China	Spatial Prioritisation	1	1	0	1	0
Approaches for aggregating preferences in participatory forest planning: An experiment with university students	Nordstrom, EM; Ohman, K; Eriksson, LO	MCDA	academic	Sweden	Threat Abatement	1	1	1	1	0
Areas of Climate Stability of Species Ranges in th	Terribile, LC; Lima-Ribeiro, MS; Araujo, MB; Biza	SCP	academic	Brazil	Spatial Prioritisation	0	1	0	1	0
Assessing conservation priorities of xenarthrans i	Tognelli, MF; Abba, AM; Bender, JB; Seitz, VP"	SCP	academic	Argentina	Spatial Prioritisation	1	1	0	1	0
Assessing the influence of different inland lake management strategies on human-mediated invasive species spread	Morandi, MJ; Manning, NF; Bossenbroek, JM; Jerde, CL	AM	academic	US	Threat Abatement	0	1	0	1	0
Assessing the performance of the existing and prop	Tognelli, MF; Fernandez, M; Marquet, PA"	SCP	academic	Chile	Spatial Prioritisation	1	1	1	1	0
Assessing the value of Earth Observation for managing coral reefs: An example from the Great Barrier Reef	Bouma, JA; Kuik, O; Dekker, AG	CE	academic	Australia	Threat Abatement	0	1	1	1	0
Balancing conservation and recreational fishery objectives for a threatened fish species, the Murray cod, Maccullochella peelii	Koehn, JD; Todd, CR	AM	conservation practice	Australia	Population Management	0	1	1	1	0
Balancing water supply and old-growth forest conservation in the lowlands of south-central Chile through adaptive co-management	Donoso, PJ; Frene, C; Flores, M; Moorman, MC; Oyarzun, CE; Zavaleta, JC	AM	conservation practice	Chile	Spatial Prioritisation	0	1	1	0	0
BAYESIAN NETWORK MODELS FOR ENVIRONMENTAL FLOW DECISION-MAKING: 1. LATROBE RIVER AUSTRALIA	Shenton, W; Hart, BT; Chan, T	AM	academic	Australia	Mixed Management	0	1	0	1	1
Bayesian Networks and Adaptive Management of Wildlife Habitat	Howes, AL; Maron, M; Mcalpine, CA	AM	conservation practice	Australia	Restoration	0	1	0	1	0
Bayesian networks for environmental flow decision-making and an application in the Yellow River estuary, China	Pang, AP; Sun, T	AM	academic	China	Restoration	1	1	1	1	1

Benefits and Challenges of Scaling Up Expansion o	Horigue, V; Pressey, RL; Mills, M; Brotankova, J;	SCP	academic	Philippines	Spatial Prioritisation	1	1	1	1	0
Benefits and Limitations of Using Decision-Analyti	van der Burg, MP; Thomas, CC; Holcombe, T; Nelson,	SDM	conservation practice	US	Threat Abatement	1	1	1	1	1
Benefits of earth observation data for conservatio	Jantke, K; Schleupner, C; Schneider, UA"	SCP	academic	Europe	Spatial Prioritisation	1	0	1	1	0
Benefits of integrating complementarity into priority threat management	Chades, I; Nicol, S; van Leeuwen, S; Walters, B; Firn, J; Reeson, A; Martin, TG; Carwardine, J	CE	conservation practice	Australia	Mixed Management	1	1	1	1	1
Biodiverse Planting for Carbon and Biodiversity on Indigenous Land	Renwick, AR; Robinson, CJ; Martin, TG; May, T; Polglase, P; Possingham, HP; Carwardine, J	mixed	academic	Australia	Mixed Management	1	1	1	1	0
Bridging the ""gap"" in systematic conservation p	Zhang, YB; Liu, YL; Fu, JX; Phillips, N; Zhang, M	SCP	academic	China	Spatial Prioritisation	1	0	1	0	0
Building robust conservation plans	Visconti, P; Joppa, L"	SCP	academic	Australia	Spatial Prioritisation	1	1	1	1	0
Can agro-ecosystems efficiently complement protect	Troupin, D; Carmel, Y"	SCP	academic	Israel	Spatial Prioritisation	1	0	1	1	0
Can the concept of ecosystem services be practically applied to improve natural resource management decisions?	Wainger, LA; King, DM; Mack, RN; Price, EW; Maslin, T	CE	conservation practice	US	Mixed Management	1	1	1	1	1
Carbon storage, timber production, and biodiversity: comparing ecosystem services with multi-criteria decision analysis	Schwenk, WS; Donovan, TM; Keeton, WS; Nunery, JS	MCDA	academic	US	NA	1	1	1	1	1
Catchment zoning to unlock freshwater conservation	Hermoso, V; Filipe, AF; Segurado, P; Beja, P"	SCP	academic	Spain, Portugal	Spatial Prioritisation	1	1	1	1	0
Coarse-filter surrogates do not represent freshwa	Januchowski-Hartley, SR; Hermoso, V; Pressey, RL;	SCP	academic	Australia	Spatial Prioritisation	1	0	1	1	0
Collaborative Adaptive Rangeland Management Fosters Management-Science Partnerships	Wilmer, H; Derner, JD; Fernandez-Gimenez, ME; Briske, DD; Augustine, DJ; Porensky, LM	AM	conservation practice	US	Threat Abatement	1	1	1	1	0
Collaborative decision-analytic framework to maxim	Thorne, KM; Mattsson, BJ; Takekawa, J; Cummings, J	SDM	conservation practice	US	Mixed Management	1	1	1	1	1

Combined Use of Systematic Conservation Planning,	Fajardo, J; Lessmann, J; Bonaccorso, E; Devenish,	SCP	academic	Peru	Spatial Prioritisation	1	1	1	1	0
Combining Structured Decision Making and Value-of-	Moore, JL; Runge, MC	mixed	conservation practice	Australia	Mixed Management	1	1	1	1	0
Comparative hazard assessment for protected species in a fire-prone landscape	Roloff, GJ; Mealey, SP; Bailey, JD	AM	academic	US	Threat Abatement	0	1	0	1	0
Comparing alternative systematic conservation plan	Meynard, CN; Howell, CA; Quinn, JF"	SCP	academic	Chile	Spatial Prioritisation	1	0	1	1	0
Comparing and Integrating Community-Based and Scie	Ban, NC; Picard, CR; Vincent, ACJ"	SCP	conservation practice	Canada	Spatial Prioritisation	1	1	1	1	0
Comparing habitat configuration strategies for ret	Mokany, K; Harwood, TD; Ferrier, S"	SCP	academic	Australia	Spatial Prioritisation	1	1	0	1	0
Comparing land-use alternatives: Using the ecosystem services concept to define a multi-criteria decision analysis	Fontana, V; Radtke, A; Fedrigotti, VB; Tappeiner, U; Tasser, E; Zerbe, S; Buchholz, T	MCDA	academic	Austria	NA	1	1	1	1	0
Comparing Methods for Prioritising Protected Areas	Gardner, CJ; Raxworthy, CJ; Metcalfe, K; Raselima	SCP	academic	Madagascar	Spatial Prioritisation	1	1	0	1	0
Complex decisions made simple: a primer on stochastic dynamic programming	Marescot, L; Chapron, G; Chades, I; Fackler, PL; Duchamp, C; Marboutin, E; Gimenez, O	AM	academic	France	Population Management	1	0	0	1	0
Concept for cost effective improvement of river morphology in the context of the European Water Framework Directive	Klauer, B; Schiller, J; Bathe, F	mixed	academic	Germany	Mixed Management	1	1	1	0	0
Conceptual basis for an integrated system for the management of a protected area. Examples from its application in a mediterranean area	Cornejo, E; Fungairino, SG; Barandica, JM; Serrano, JM; Zorrilla, JM; Gomez, T; Zapata, FJ; Acosta, FJ	mixed	conservation practice	Spain	Management not specified	1	0	1	0	0
Conceptual framework for adaptive management of coupled human and natural systems with respect to climate change uncertainty	Prato, T	AM	academic	theoretical	Management not specified	1	0	1	0	0
Confronting dynamics and uncertainty in optimal decision making for conservation	Williams, BK; Johnson, FA	SCP	academic	theoretical	Spatial Prioritisation	1	0	1	1	0
Confronting dynamics and uncertainty in optimal decision making for conservation	Williams, BK; Johnson, FA	AM	academic	theoretical	Mixed Management	1	1	1	1	0

Conservation in the face of climate change: The roles of alternative models, monitoring, and adaptation in confronting and reducing uncertainty	Conroy, MJ; Runge, MC; Nichols, JD; Stodola, KW; Cooper, RJ	mixed	academic	US	Mixed Management	1	1	1	0	0
Conservation of grassland butterflies in Finland under a changing climate	Tainio, A; Heikkinen, RK; Heliola, J; Hunt, A; Watkiss, P; Fronzek, S; Leikola, N; Lotjonen, S; Mashkina, O; Carter, TR	CE	conservation practice	Finland	Mixed Management	1	1	1	1	0
Conservation of northern bobwhite on private lands in Georgia, USA under uncertainty about landscape-level habitat effects	Howell, JE; Moore, CT; Conroy, MJ; Hamrick, RG; Cooper, RJ; Thackston, RE; Carroll, JP	AM	academic	US	Restoration	0	1	0	1	0
Conservation planning for freshwater ecosystems in	Lira-Noriega, A; Aguilar, V; Alarcon, J; Kolb, M;	SCP	academic	Mexico	Spatial Prioritisation	1	1	1	0	1
Conservation planning for imperiled aquatic species in an urbanizing environment	Wenger, SJ; Freeman, MC; Fowler, LA; Freeman, BJ; Peterson, JT	AM	conservation practice	US	Threat Abatement	1	1	0	1	0
Conservation planning for successional landscapes	Drechsler, M; Lourival, R; Possingham, HP"	SCP	academic	NA	Spatial Prioritisation	1	1	0	1	0
Conservation planning in agricultural landscapes:	Shackelford, GE; Steward, PR; German, RN; Sait, S	SCP	academic	global	Spatial Prioritisation	1	1	1	1	0
Conservation planning on a budget: a ""resource l	Didier, KA; Wilkie, D; Douglas-Hamilton, I; Frank	mixed	conservation practice	Kenya	Spatial Prioritisation	1	1	1	0	0
Conservation planning under uncertainty in urban d	Troupin, D; Carmel, Y"	SCP	academic	Israel	Spatial Prioritisation	1	1	1	1	0
Conservation planning with insects at three differ	Cabeza, M; Arponen, A; Jaattela, L; Kujala, H; va	SCP	academic	Finland	Spatial Prioritisation	1	1	0	1	0
Conservation planning with insects at three differ	Cabeza, M; Arponen, A; Jaattela, L; Kujala, H; va	SCP	academic	Finland	Mixed Management	1	1	1	1	0
Conservation planning with insects at three differ	Cabeza, M; Arponen, A; Jaattela, L; Kujala, H; va	SCP	academic	Finland	Mixed Management	1	0	1	1	1
Conservation Planning with Multiple Organizations	Bode, M; Probert, W; Turner, WR; Wilson, KA; Vent	SCP	academic	NA	Spatial Prioritisation	1	0	1	1	1
Conservation priorities for the threatened flora o	Monteiro, L; Machado, N; Martins, E; Pougy, N; Ve	SCP	academic	Brazil	Spatial Prioritisation	1	1	1	0	0
Conservation priority of global Galliformes specie	Chen, YH"	SCP	academic	global	Spatial Prioritisation	1	0	0	0	0
Conserving what, where and how? Cost-efficient me	Petersen, AH; Strange, N; Anthon,	SCP	academic	Denmark	Spatial Prioritisation	1	1	1	1	0

	S; Bjorner, TB;									
ConsNet-A tabu search approach to the spatially co	Ciarleglio, M; Barnes, JW; Sarkar, S"	SCP	academic	Mexico	Spatial Prioritisation	1	0	0	1	0
Controlling range expansion in habitat networks by adaptively targeting source populations	Hock, K; Wolff, NH; Beeden, R; Hoey, J; Condie, SA; Anthony, KRN; Possingham, HP; Mumby, PJ	mixed	academic	Australia	Threat Abatement	1	1	1	1	0
Cost and feasibility of a barrier to halt the spre	Southwell, D; Tingley, R; Bode, M; Nicholson, E; P	mixed	conservation practice	Australia	Threat Abatement	0	1	1	1	0
Cost-effective conservation of amphibian ecology a	Campos, FS; Lourenco-de-Moraes, R; Llorente, GA;	SCP	academic	Brazil	Spatial Prioritisation	0	1	1	1	0
Cost-effective conservation of an endangered frog under uncertainty	Rose, LE; Heard, GW; Chee, YE; Wintle, BA	CE	academic	Australia	NA	1	1	1	1	0
Cost-effective ecological restoration	Kimball, S; Lulow, M; Sorenson, Q; Balazs, K; Fang, YC; Davis, SJ; O'Connell, M; Huxman, TE	CE	academic	US	Restoration	1	1	1	1	0
Cost-Effective Marine Protection - A Pragmatic Approach	Oinonen, S; Hyytiainen, K; Ahlvik, L; Laamanen, M; Lehtoranta, V; Salojarvi, J; Virtanen, J	CE	conservation practice	Finland	Mixed Management	1	1	1	1	0
Cost-Effectiveness Analysis of Sandhill Crane Habitat Management	Kessler, AC; Merchant, JW; Shultz, SD; Allen, CR	CE	academic	US	Mixed Management	1	1	1	1	0
Could European marine conservation policy benefit	Giakoumi, S; Katsanevakis, S; Vassilopoulou, V; P	SCP	academic	Greece	Spatial Prioritisation	1	0	1	1	1
Coupling hydrologic and economic modeling for wetland management multi-optimization in Tram Chim National Park, Vietnam	Nguyen, TTN; Migliaccio, KW; Evans, EA; Martinez, CJ; Sansalone, JJ; Clark, MW	MCDA	academic	Vietnam	NA	1	0	1	1	0
Coverage of vertebrate species distributions by Im	Kukkala, AS; Santangeli, A; Butchart, SHM; Maiora	SCP	academic	Europe	Spatial Prioritisation	1	0	0	0	0
Creating Larger and Better Connected Protected Areas Enhances the Persistence of Big Game Species in the Maputaland-Pondoland-Albany Biodiversity Hotspot	Di Minin, E; Hunter, LTB; Balme, GA; Smith, RJ; Goodman, PS; Slotow, R	MCDA	academic	South Africa	Spatial Prioritisation	1	1	0	1	0

Critical catchments for freshwater biodiversity c	Carrizo, SF; Lengyel, S; Kapusi, F; Szabolcs, M;	SCP	academic	Europe	Spatial Prioritisation	1	0	1	1	0
Decision analysis for habitat conservation of an e	Robinson, OJ; McGowan, CP; Apodaca, JJ	SDM	conservation practice	US	Spatial Prioritisation	1	1	1	1	1
Decision analysis for species preservation under sea-level rise	Linhoss, AC; Kiker, GA; Aiello-Lammens, ME; Chu-Agor, ML; Convertino, M; Munoz-Carpena, R; Fischer, R; Linkov, I	MCDA	academic	US	Mixed Management	0	1	1	1	0
Decision Support System for Adaptive Regional-Scale Forest Management by Multiple Decision-Makers	Yamada, Y; Yamaura, Y	AM	academic	Japan	Population Management	0	1	1	1	0
Defining conservation priorities for freshwater f	Strecker, AL; Olden, JD; Whittier, JB; Paukert, C	SCP	academic	US	Spatial Prioritisation	1	1	0	1	1
Defining spatial conservation priorities in the fa	Faleiro, FV; Machado, RB; Loyola, RD"	SCP	academic	Brazil	Spatial Prioritisation	1	1	0	1	0
Delimiting priority areas for the conservation of	de Carvalho, DL; Sousa-Neves, T; Cerqueira, PV; G	SCP	academic	Brazil	Spatial Prioritisation	1	0	0	1	0
DELIVERY OF ENVIRONMENTAL WATER UNDER CONTENTIOUS WATER REFORM. LEARNING BY DOING TO IMPROVE WATER DELIVERY AND GOVERNMENT-MANAGER-COMMUNITY-SCIENTIST WORKING RELATIONSHIPS	Conallin, J	AM	conservation practice	Australia	Restoration	1	1	1	0	0
Designing a conservation area network that support	Nel, JL; Reyers, B; Roux, DJ; Impson, ND; Cowling	SCP	conservation practice	South Africa	Spatial Prioritisation	1	0	1	0	0
Designing a network of green infrastructure to enhance the conservation value of protected areas and maintain ecosystem services	Lanzas, M; Hermoso, V; de-Miguel, S; Bota, G; Bro	SCP	academic	Spain	Spatial Prioritisation	1	0	1	1	1
Designing a network of marine reserves in the Medi	Giakoumi, S; Grantham, HS; Kokkoris, GD; Possingh	SCP	academic	Greece	Spatial Prioritisation	1	0	1	1	0
Designing a resilient network of marine protected	Green, A; Smith, SE; Lipsett-Moore, G; Groves, C;	SCP	conservation practice	Papua New Guinea	Spatial Prioritisation	1	1	1	1	0

Designing connected marine reserves in the face of	Alvarez-Romero, JG; Munguia-Vega, A; Beger, M; Ma	SCP	academic	US	Spatial Prioritisation	1	1	1	1	1
Designing natural heritage systems in southern Ont	Puric-Mladenovic, D; Strobl, S"	SCP	conservation practice	US	Spatial Prioritisation	1	0	1	1	0
Designing protected area networks that translate i	Bicknell, JE; Collins, MB; Pickles, RSA; McCann,	SCP	conservation practice	Guyana	Spatial Prioritisation	1	0	1	1	0
Desktop classification of inland wetlands for sys	Van Deventer, H; Nel, J; Mbona, N; Job, N; Ewart-	SCP	academic	South Africa	Spatial Prioritisation	1	1	0	0	0
Determination of priority nature conservation are	Zhang, L; Xu, WH; Ouyang, ZY; Zhu, CQ"	SCP	academic	China	Spatial Prioritisation	1	1	0	1	0
Determining When to Change Course in Management Actions	Ng, CF; Mccarthy, MA; Martin, TG; Possingham, HP	AM	academic	Australia	Population Management	1	0	0	1	0
Developing a conservation strategy to maximize persistence of an endangered freshwater mussel species while considering management effectiveness and cost	Smith, DR; Mcrae, SE; Augspurger, T; Ratcliffe, JA; Nichols, RB; Eads, CB; Savidge, T; Bogan, AE	SDM	conservation practice	US	Mixed Management	1	1	1	1	1
Developing a landscape-scale, multi-species, and c	Smith, DR; Butler, RS; Jones, JW; Gatenby, CM; Hyl	SDM	academic	US	Mixed Management	1	1	1	1	1
Developing a population target for an overabundant ungulate for ecosystem restoration	Serrouya, R; McLellan, BN; Boutin, S; Seip, DR; Nielsen, SE	AM	academic	Canada	Mixed Management	1	1	0	1	0
Developing an Adaptive Management approach to prescribed burning: a long-term heathland conservation experiment in north-west Italy	Ascoli, D; Beghin, R; Ceccato, R; Gorlier, A; Lombardi, G; Lonati, M; Marzano, R; Bovio, G; Cavallero, A	AM	academic	Italy	Population Management	0	1	0	1	0
Developing conservation strategies for Pinus korai	Wan, JZ; Wang, CJ; Yu, JH; Nie, SM; Han, SJ; Liu,	SCP	academic	China	Spatial Prioritisation	1	1	1	1	0
Development and testing of an object-oriented model for adaptively managing human disturbance of least tern (Sternula antillarum) nesting habitat	Kanapaux, W; Kiker, GA	AM	academic	US	Threat Abatement	1	1	0	1	0
Development of a cost-effective diversity-maximising decision-support tool for in situ	Samuel, AF; Drucker, AG; Andersen, SB; Simianer, H; van	CE	academic	Latiname rica	NA	0	1	1	0	0

crop genetic resources conservation: The case of cacao	Zonneveld, M									
Direct Application of Invasive Species Prioritization: The Spatial Invasive Infestation and Priority Analysis Mode	Stone, D; Andreu, M	AM	academic	US	Threat Abatement	0	1	0	1	0
Distinguishing Values From Science in Decision Mak	Mitchell, MS; Cooley, H; Gude, JA; Kolbe, J; Nowak	SDM	conservation practice	US	Population Management	1	1	1	1	1
Does supplemental feeding affect the viability of translocated populations? The example of the hihi	Chauvenet, ALM; Ewen, JG; Armstrong, DP; Coulson, T; Blackburn, TM; Adams, L; Walker, LK; Pettorelli, N	AM	academic	New Zealand	Population Management	1	1	0	0	0
Dynamic marine protected areas can improve the resilience of coral reef systems	Game, ET; Bode, M; McDonald-Madden, E; Grantham, HS; Possingham, HP	mixed	academic	Western Indian Ocean	Mixed Management	1	1	0	1	1
Ecological coherence of marine protected area networks: a spatial assessment using species distribution models	Sundblad, G; Bergstrom, U; Sandstrom, A	SCP	academic	Baltic Sea	Spatial Prioritisation	1	1	0	1	0
Economic returns of groundwater management sustaining an ecosystem service of dust suppression by alkali meadow in Owens Valley, California	Gutrich, JJ; Gigliello, K; Gardner, KV; Elmore, AJ	mixed	academic	US	Mixed Management	0	1	1	1	1
Economics of camel control in central Australia	Drucker, AG; Edwards, GP; Saalfeld, WK	CE	academic	Australia	Threat Abatement	1	1	1	1	0
Economies of Scope in the Agricultural Provision of Ecosystem Services: An Application to a High Cost Production Region	Huber, R; Lehmann, B	CE	academic	Switzerla nd	Mixed Management	1	1	1	1	0
Ecosystem Services in Conservation Planning: Targe	Chan, KMA; Hoshizaki, L; Klinkenberg, B"	SCP	academic	Canada	Spatial Prioritisation	1	0	1	1	0
Effect of risk aversion on prioritizing conservation projects	Tulloch, AIT; Maloney, RF; Joseph, LN; Bennett, JR; Di Fonzo, MMI; Probert, WJM; O'Connor, SM; Densem, JP; Possingham, HP	CE	academic	New Zealand	NA	1	1	1	1	1

Effective use of data from monitoring programs and field studies for conservation decision making: predictions, designs and models working together	Conroy, MJ; Stodola, KW; Cooper, RJ	AM	conservation practice	US	Mixed Management	1	1	0	1	0
Effects of budget constraints on conservation netw	Remme, RP; Schroter, M"	SCP	academic	Netherlands	Spatial Prioritisation	1	0	1	1	0
EFFECTS OF FLOW DYNAMICS ON THE AQUATIC-TERRESTRIAL TRANSITION ZONE (ATTZ) OF LOWER MISSOURI RIVER SANDBARS WITH IMPLICATIONS FOR SELECTED BIOTA	Tracy-Smith, E; Galat, DL; Jacobson, RB	AM	academic	US	Restoration	0	1	0	1	0
Effects of Targeted Grazing and Prescribed Burning on Community and Seed Dynamics of a Downy Brome (Bromus tectorum)-Dominated Landscape	Diamond, JM; Call, CA; Devoe, N	AM	academic	US	Threat Abatement	0	1	0	1	0
Effects of threat management interactions on conservation priorities	Auerbach, NA; Wilson, KA; Tulloch, AIT; Rhodes, JR; Hanson, JO; Possingham, HP	CE	academic	Australia	Threat Abatement	1	1	1	1	1
Efficient and equitable design of marine protected	Gurney, GG; Pressey, RL; Ban, NC; Alvarez-Romero,	SCP	academic	Fiji	Spatial Prioritisation	1	1	1	1	1
Efficient Use of Information in Adaptive Management with an Application to Managing Recreation near Golden Eagle Nesting Sites	Fackler, PL; Pacifici, K; Martin, J; McIntyre, C	AM	academic	US	Threat Abatement	1	1	1	1	0
Enhanced Adaptive Management: Integrating Decision Analysis, Scenario Analysis and Environmental Modeling for the Everglades	Convertino, M; Foran, CM; Keisler, JM; Scarlett, L; LoSchiavo, A; Kiker, GA; Linkov, I	AM	academic	US	Restoration	1	1	1	1	1
Ensuring local stakeholder support for marine cons	Syakur, A; Wibowo, JT; Firmansyah, F; Azam, I; Li	SCP	conservation practice	Indonesia	Spatial Prioritisation	1	1	1	1	0
Eradicating the grey squirrel Sciurus carolinensis	La Morgia, V; Paoloni, D; Genovesi, P	mixed	conservation practice	Italy	Threat Abatement	0	1	1	1	0
Evaluating a focal-species approach for tidal mars	Klingbeil, BT; Cohen, JB; Correll, MD; Field, CR;	SCP	academic	US	Spatial Prioritisation	1	1	1	1	0
Evaluating and managing wildlife impacts of climate change under uncertainty	Prato, T	AM	academic	theoretical	Mixed Management	1	1	1	1	0

Evaluating complementary networks of restoration p	Ikin, K; Tulloch, A; Gibbons, P; Ansell, D; Seddo	SCP	academic	Australia	Mixed Management	1	0	1	1	0
Evaluating conservation and fisheries management s	Metcalfe, K; Vaz, S; Engelhard, GH; Villanueva, M	SCP	academic	UK, France	Spatial Prioritisation	1	1	1	1	1
Evaluating trade-offs in bull trout reintroduction strategies using structured decision making	Brignon, WR; Peterson, JT; Dunham, JB; Schaller, HA; Schreck, CB	SDM	academic	US	Population Management	1	0	0	1	1
Evaluation of Potential Responses to Invasive Non-	Liu, S; Walshe, T; Long, G; Cook, D	SDM	conservation practice	Australia	Threat Abatement	1	1	1	1	1
Evidence-based marine protected area planning for	Schofield, G; Scott, R; Dimadi, A; Fossette, S; K	SCP	conservation practice	Greece	Spatial Prioritisation	1	0	1	0	1
Expanding protected areas beyond their terrestrial	Nel, JL; Reyers, B; Roux, DJ; Cowlingc, RM"	SCP	conservation practice	South Africa	Spatial Prioritisation	1	1	0	0	0
Expert Elicitation, Uncertainty, and the Value of Information in Controlling. Invasive Species	Johnson, FA; Smith, BJ; Bonneau, M; Martin, J; Romagosa, C; Mazzotti, F; Waddle, H; Reed, RN; Eckles, JK; Vitt, LJ	CE	academic	US	Threat Abatement	0	1	1	1	1
Exploring a Resilience-Based Approach to Spatial Planning in Fathom Five National Marine Park, Lake Huron, Canada, using Marxan with Zones	Parker, SR; Truscott, J; Harpur, C; Murphy, SD	SCP	academic	Canada	Spatial Prioritisation	1	0	1	1	0
Exploring spatial patterns of vulnerability for di	Vimal, R; Pluvinet, P; Sacca, C; Mazagol, PO; Etl	SCP	academic	France	Spatial Prioritisation	1	1	0	1	0
Exploring the environmental value of ecosystem services for a river basin through a spatial multicriteria analysis	Comino, E; Bottero, M; Pomarico, S; Rosso, M	MCDA	academic	Italy	Spatial Prioritisation	0	1	0	1	0
Facilitating adaptation of biodiversity to climate change: a conceptual framework applied to the world's largest Mediterranean-climate woodland	Prober, SM; Thiele, KR; Rundel, PW; Yates, CJ; Berry, SL; Byrne, M; Christidis, L; Gosper, CR; Grierson, PF; Lemson, K; Lyons, T; Macfarlane, C; O'Connor, MH; Scott, JK; Standish, RJ; Stock, WD; van Etten, EJB; Wardell-Johnson,	AM	academic	Australia	Mixed Management	1	1	1	0	0

	GW; Watson, A									
Fast, slow, and adaptive management of habitat modification-invasion interactions: woodland caribou (Rangifer tarandus)	Wilman, EA; Wilman, EN	AM	academic	Canada	Threat Abatement	1	1	0	0	0
Fishery failure, unemployed commercial fishers, and lost blue crab pots: An unexpected success story	Havens, K; Bilkovic, DM; Stanhope, D; Angstadt, K	AM	conservation practice	US	Mixed Management	0	1	1	0	0
Forecasting the Effects of Land Use Scenarios on Farmland Birds Reveal a Potential Mitigation of Climate Change Impacts	Prince, K; Lorrilliere, R; Barbet-Massin, M; Leger, F; Jlguet, F	AM	academic	France	Threat Abatement	0	1	0	1	0
Forest restoration in a surface fire-dependent ecosystem: An example from a mixed conifer forest, southwestern Colorado, USA	Korb, JE; Fule, PZ; Stoddard, MT	AM	academic	US	Restoration	0	1	1	1	0
From Marxan to management: ocean zoning with stak	Jumin, R; Binson, A; Mcgowan, J; MaGupin, S; Bege	SCP	conservation practice	Malaysia	Spatial Prioritisation	1	1	1	0	0
From Population Viability Analysis to Coviability of Farmland Biodiversity and Agriculture	Mouysset, L; Doyen, L; Jiguet, F	AM	academic	France	NA	1	1	1	1	0
From principles to practice: a spatial approach to	Wedding, LM; Friedlander, AM; Kittinger, JN; Watl	SCP	conservation practice	North Pacific	Spatial Prioritisation	1	1	1	0	1
Fuzzy adaptive management of social and ecological carrying capacities for protected areas	Prato, T	AM	academic	theoretic al	Threat Abatement	1	1	1	1	0
Gap analysis of European wetland species: priority	Jantke, K; Schleupner, C; Schneider, UA"	SCP	academic	Europe	Spatial Prioritisation	1	0	1	1	1
Genecological zones and selection criteria for natural forest populations for conservation: the case of Boswellia papyrifera in Ethiopia	Derero, A; Worku, A; Kassa, H	MCDA	academic	Ethiopia	Spatial Prioritisation	0	1	1	1	0

Global conservation strategies for two clades of s	Terribile, LC; de Oliveira, G; Albuquerque, F; Ro	SCP	academic	global	Spatial Prioritisation	1	1	0	1	0
GMSE: An r package for generalised management strategy evaluation	Duthie, AB; Cusack, JJ; Jones, IL; Minderman, J; Nilsen, EB; Pozo, RA; Rakotonarivo, OS; Van Moorter, B; Bunnefeld, N	AM	academic	theoretical	Population Management	1	1	1	0	1
Governance factors in the identification of global	Eklund, J; Arponen, A; Visconti, P; Cabeza, M"	SCP	academic	global	Spatial Prioritisation	1	0	1	1	1
Handling overheads: optimal multi-method invasive	Baker, CM; Armsworth, PR; Lenhart, SM	CE	academic	NA	Threat Abatement	0	1	1	1	0
He who hesitates is lost: Why conservation in the	Portman, ME; Notarbartolo-di-Sciara, G; Agardy, T	SCP	academic	Europe	Mixed Management	1	1	1	0	0
How does the inclusion of Data Deficient species c	Trindade, J; de Carvalho, RA; Brito, D; Loyola, R	SCP	academic	Brazil	Spatial Prioritisation	1	0	1	1	0
Identification of a spatially efficient portfolio	Geselbracht, L; Torres, R; Cumming, GS; Dorfman,	SCP	academic	US	Spatial Prioritisation	1	1	0	1	0
Identification of Prime Butterfly Areas in Turkey	Zeydanli, US; Turak, AS; Balkiz, O; Ozut, D; Ertu	SCP	academic	Turkey	Spatial Prioritisation	1	0	1	1	0
Identification of top priority areas and managemen	Mikkonen, N; Moilanen, A"	SCP	conservation practice	Finland	Spatial Prioritisation	1	0	0	0	0
Identifying a network of priority areas for conser	Solovyev, B; Spiridonov, V; Onufrenya, I; Belikov	SCP	academic	Russia	Spatial Prioritisation	1	0	1	1	0
Identifying a preservation zone using multi-criteria decision analysis	Farashi, A; Naderi, M; Parvian, N	MCDA	academic	Iran	Spatial Prioritisation	0	1	1	0	1
Identifying and mapping biodiversity processes for	Lagabrielle, E; Rouget, M; Payet, K; Wistebaar, N	SCP	academic	Reunion Island	Spatial Prioritisation	1	1	1	1	0
Identifying conservation priorities and managemen	Qu, Y; Lu, M"	SCP	academic	China	Spatial Prioritisation	1	1	1	0	0
Identifying effective actions to guide volunteer-based and nationwide conservation efforts for a ground-nesting farmland bird	Santangeli, A; Arroyo, B; Millon, A; Bretagnolle, V	CE	academic	France	Threat Abatement	0	1	1	1	0
Identifying high-value areas to strengthen marine	Vila, AR; Falabella, V; Galvez, M; Farias, A; Dro	SCP	conservation practice	Chile, Argentina	Spatial Prioritisation	1	0	1	1	0
Identifying target reference points for harvesting	Stevens, BS; Bence, JR; Porter, WF; Jones, ML	SDM	conservation practice	US	Population Management	1	1	1	1	0

Implementation of a framework for multi-species, m	McGowan, CP; Smith, DR; Nichols, JD; Lyons, JE; Sw	mixed	conservation practice	US	Population Management	1	1	1	1	0
Implementation of Environmental Flows for Intermittent River Systems: Adaptive Management and Stakeholder Participation Facilitate Implementation	Conallin, J; Wilson, E; Campbell, J	AM	conservation practice	Australia	Restoration	1	1	1	1	1
Implementation of the European Water Framework Directive: procedures and a simple model for the identification of the most cost-effective measures in eutrophicated catchments	Zanou, B; Bellas, C; Skourtos, M	CE	academic	Europe	Threat Abatement	0	1	1	1	0
Implementation of the first adaptive management plan for a European migratory waterbird population: The case of the Svalbard pink-footed goose Anser brachyrhynchus	Madsen, J; Williams, JH; Johnson, FA; Tombre, IM; Dereliev, S; Kuijken, E	mixed	conservation practice	Norway, Denmark, Netherlands, Belgium	Mixed Management	1	1	1	1	0
Implementing comprehensiveness, adequacy and repr	Sharafi, SM; White, M; Burgman, M"	SCP	academic	Australia	Spatial Prioritisation	0	0	0	1	0
Improving bioregional frameworks for conservation	Bino, G; Ramp, D; Kingsford, RT"	SCP	academic	Australia	Spatial Prioritisation	1	0	1	1	0
Improving effectiveness of systematic conservation	Veloz, S; Salas, L; Altman, B; Alexander, J; Jong	SCP	academic	US	Spatial Prioritisation	1	0	0	1	0
Improving Identification of Areas for Ecological Restoration for Conservation by Integrating USLE and MCDA in a GIS-Environment: A Pilot Study in a Priority Region Northern Mexico	Aguirre-Salado, CA; Miranda-Aragon, L; Pompa-Garcia, M; Reyes-Hernandez, H; Soubervielle-Montalvo, C; Flores-Cano, JA; Mendez-Cortes, H	MCDA	academic	Mexico	Mixed Management	0	1	0	0	0
Improving spatial prioritisation for remote marine	Moore, CH; Radford, BT; Possingham, HP; Heyward,	SCP	conservation practice	Australia	Spatial Prioritisation	1	1	1	1	1
Improving supplementary feeding in species conserv	Ewen, JG; Walker, L; Canessa, S; Groombridge, JJ	SDM	conservation practice	New Zealand	Population Management	1	0	1	0	0
Incentivizing Monitoring and Compliance in Trophy Hunting	Bunnefeld, N; Edwards, CTT; Atickem, A; Hailu, F; Milner-Gulland, EJ	AM	academic	Ethiopia	Population Management	1	1	1	1	1

Incorporating Allee effects into reintroduction st	Armstrong, DP; Wittmer, HU	SDM	academic	NA	Population Management	1	1	1	1	1
Incorporating asymmetric connectivity into spatial	Beger, M; Linke, S; Watts, M; Game, E; Treml, E;	SCP	academic	Australia	Spatial Prioritisation	1	0	1	1	1
Incorporating climate change adaptation into natio	Game, ET; Lipsett-Moore, G; Saxon, E; Peterson, N	SCP	academic	Papua New Guinea	Spatial Prioritisation	1	1	1	1	0
Incorporating climate change in conservation plann	Bond, NR; Thomson, JR; Reich, P"	SCP	academic	Australia	Spatial Prioritisation	1	1	0	1	1
Incorporating Community Education in the Strategy for Harpy Eagle Conservation in Panama	Curti, M; Valdez, U	AM	conservation practice	Panama	Mixed Management	0	1	0	1	0
Incorporating dynamic distributions into spatial p	Runge, CA; Tulloch, AIT; Possingham, HP; Tulloch,	SCP	academic	Australia	Spatial Prioritisation	1	0	1	1	0
Incorporating ecological and evolutionary processe	Klein, C; Wilson, K; Watts, M; Stein, J; Berry, S	SCP	academic	Australia	Spatial Prioritisation	1	0	1	1	1
Incorporating ecological functions in conservation	Decker, E; Linke, S; Hermoso, V; Geist, J"	SCP	academic	Europe	Spatial Prioritisation	1	0	1	1	0
Incorporating habitat availability into systematic	Crouzeilles, R; Beyer, HL; Mills, M; Grelle, CEV;	SCP	academic	Brazil	Mixed Management	1	1	1	1	0
Incorporating local tenure in the systematic desig	Weeks, R; Russ, GR; Bucol, AA; Alcala, AC"	SCP	academic	Philippine s	Spatial Prioritisation	1	1	1	1	1
Index-Based Cost-Effectiveness Analysis vs. Least-Cost River Basin Optimization Model: Comparison in the Selection of a Programme of Measures at the River Basin Scale	Girard, C; Rinaudo, JD; Pulido-Velazquez, M	CE	conservation practice	France	NA	1	1	1	1	0
Indicator-Driven Conservation Planning Across Ter	Pickens, BA; Mordecai, RS; Drew, CA; Alexander-Va	SCP	academic	US	Spatial Prioritisation	1	0	1	0	0
Inferential and forward projection modeling to evaluate options for controlling invasive mammals on islands	Anderson, DP; McMurtrie, P; Edge, KA; Baxter, PWJ; Byrom, AE	CE	academic	New Zealand	Threat Abatement	0	1	1	1	0
Informed opportunism for conservation planning in	Game, ET; Lipsett-Moore, G; Hamilton, R; Peterson	SCP	conservation practice	Solomon Islands	Spatial Prioritisation	1	0	1	1	0
Informing Canada's commitment to biodiversity cons	Coristine, LE; Jacob, AL; Schuster, R; Otto, SP;	SCP	academic	Canada	Spatial Prioritisation	0	1	0	1	0
Informing management with monitoring data: the value of	Ketz, AC; Johnson, TL; Monello, RJ; Hobbs, NT	AM	conservation practice	US	Population Management	1	1	0	1	0

Bayesian forecasting										
Insight into distribution patterns and conservati	Zhang, HX; Zhang, ML"	SCP	academic	China	Spatial Prioritisation	1	0	0	0	0
Institutional challenges of adopting ecosystem-based adaptation to climate change	Lukasiewicz, A; Pittock, J; Finlayson, M	AM	conservation practice	Australia	Mixed Management	0	1	1	0	0
Integrated Ecological Modeling and Decision Analysis Within the Everglades Landscape	Fitz, HC; Kiker, GA; Kim, JB	MCDA	conservation practice	US	Restoration	1	1	0	1	1
Integrated maps of biodiversity in the Qinling Mou	Zhang, YB; Wang, YZ; Phillips, N; Ma, KP; Li, JS;	SCP	academic	China	Spatial Prioritisation	1	1	1	1	0
Integrated modeling of oil spill response strategies: a coastal management case study	Liu, X	mixed	academic	Germany	Threat Abatement	1	1	1	1	0
Integrating a participatory process with a GIS-based multi-criteria decision analysis for protected area zoning in China	Zhang, ZM; Sherman, R; Yang, ZJ; Wu, RD; Wang, WL; Yin, M; Yang, GH; Ou, XK	MCDA	conservation practice	China	Spatial Prioritisation	0	1	1	0	0
Integrating conservation and economic objectives i	Geange, SW; Leathwick, J; Linwood, M; Curtis, H;	SCP	academic	New Zealand	Spatial Prioritisation	1	0	1	1	1
Integrating ecosystem services in river basin management plans	Terrado, M; Momblanch, A; Bardina, M; Boithias, L; Munne, A; Sabater, S; Solera, A; Acuna, V	CE	academic	Spain	Mixed Management	1	1	1	1	1
Integrating ecosystem services into environmental impact assessment: An analytic-deliberative approach	Karjalainen, TP; Marttunen, M; Sarkki, S; Rytkonen, AM	MCDA	conservation practice	Finland	Restoration	1	1	1	1	1
Integrating freshwater and terrestrial priorities	Amis, MA; Rouget, M; Lotter, M; Day, J"	SCP	academic	South Africa	Spatial Prioritisation	1	0	0	1	0
Integrating Land Market Feedbacks into Conservatio	Jantke, K; Schneider, U"	SCP	academic	Europe	Spatial Prioritisation	1	0	1	1	0
Integrating multidirectional connectivity requirem	Hermoso, V; Kennard, MJ; Linke, S"	SCP	academic	Australia	Spatial Prioritisation	1	0	1	1	0
Integrating Social Values and Ecosystem Services i	Lin, YP; Lin, WC; Li, HY; Wang, YC; Hsu, CC; Lien	SCP	academic	Taiwan	Spatial Prioritisation	1	1	1	1	1
Integrating species life-history traits and patter	Becker, CG; Loyola, RD; Haddad, CFB; Zamudio, KR"	SCP	academic	Brazil	Spatial Prioritisation	1	1	0	1	0
Integrating Stakeholder	Uribe, D; Geneletti, D;	MCDA	academic	Mexico	Restoration	1	1	0	0	0

Preferences and GIS-Based Multicriteria Analysis to Identify Forest Landscape Restoration Priorities	del Castillo, RF; Orsi, F									
Integrating wildlife conservation with conflicting	Junker, J; Boesch, C; Freeman, T; Mundry, R; Step	SCP	conservation practice	Liberia	Spatial Prioritisation	1	1	1	1	0
Integrating within-catchment and interbasin connec	Li, XW; Shi, JB; Song, XL; Ma, TT; Man, Y; Cui, B	SCP	academic	China	Spatial Prioritisation	1	1	1	1	0
Integration of landscape-scale and site-scale metrics for prioritising investments in natural capital	Crossman, ND; Bryan, BA; King, D	MCDA	conservation practice	Australia	Mixed Management	1	1	1	1	0
Interspecific Interactions May Influence Reef Fish Management Strategies in the Gulf of Mexico	Masi, MD; Ainsworth, CH; Kaplan, IC; Schirripa, MJ	AM	academic	US	Population Management	0	1	1	1	1
Keeping All the PIECES: Phylogenetically Informed Ex Situ Conservation of Endangered Species	Larkin, DJ; Jacobi, SK; Hipp, AL; Kramer, AT	MCDA	academic	US	Mixed Management	1	1	0	1	1
Landscape Planning for Agricultural Non-Point Source Pollution Reduction. II. Balancing Watershed Size, Number of Watersheds, and Implementation Effort	Maxted, J; Diebel, M; Vander Zanden, M	mixed	academic	US	Threat Abatement	1	1	1	1	1
Landscape-scale conservation design across biotic	Leonard, PB; Baldwin, RF; Hanks, RD"	SCP	conservation practice	US	Spatial Prioritisation	1	1	1	1	0
Landscape-scale spatial planning at WWF: a variety	Morrison, J; Loucks, C; Long, B; Wikramanayake, E	SCP	conservation practice	Indonesia, Papua New Guinea	Spatial Prioritisation	1	0	1	0	0
Landscape-scale spatial planning at WWF: a variety	Morrison, J; Loucks, C; Long, B; Wikramanayake, E	SCP	conservation practice	Vietnam	Spatial Prioritisation	1	1	1	1	0
Landscape-scale spatial planning at WWF: a variety	Morrison, J; Loucks, C; Long, B; Wikramanayake, E	SCP	conservation practice	India, Nepal	Mixed Management	1	0	1	0	0
Landscapes Toolkit: an integrated modelling framework to assist stakeholders in exploring options for sustainable landscape development	Bohnet, IC; Roebeling, PC; Williams, KJ; Holzworth, D; van Grieken, ME; Pert, PL; Kroon, FJ; Westcott, DA; Brodie, J	AM	conservation practice	Australia	Mixed Management	1	1	1	1	1
Large expansion of oil industry in the Ecuadorian	Lessmann, J; Fajardo, J; Munoz, J; Bonaccorso, E"	SCP	academic	Ecuador	Spatial Prioritisation	1	1	1	1	0

Large-scale conservation planning in a multination	Mazor, T; Giakoumi, S; Kark, S; Possingham, HP"	SCP	academic	Europe	Spatial Prioritisation	1	0	1	1	0
Learning about colonization when managing metapopulations under an adaptive management framework	Southwell, DM; Hauser, CE; McCarthy, MA	AM	academic	US	Restoration	1	1	0	1	0
Linking modelling, monitoring and management: an integrated approach to controlling overabundant wildlife	Chee, YE; Wintle, BA	AM	academic	Australia	Threat Abatement	0	1	0	1	0
Linking planetary boundaries and ecosystem accounting, with an illustration for the Colombian Orinoco river basin	Vargas, L; Willemen, L; Hein, L	AM	academic	Colombia	Threat Abatement	1	1	1	0	0
Linking regional planning and local action: Toward	Mills, M; Alvarez-Romero, JG; Vance-Borland, K; C	SCP	academic	Solomon Islands	Spatial Prioritisation	1	0	1	1	0
Making the best use of experts' estimates to prioritise monitoring and management actions: A freshwater case study	Nicol, S; Ward, K; Stratford, D; Joehnk, KD; Chades, I	AM	conservation practice	Australia	Restoration	1	1	0	1	1
Making the leap from science to implementation: Strategic agricultural conservation in Michigan's Saginaw Bay watershed	Fales, M; Dell, R; Herbert, ME; Sowa, SP; Asher, J; O'Neil, G; Doran, PJ; Wickerham, B	CE	conservation practice	US	Threat Abatement	0	1	1	0	0
Making the leap from science to implementation: Strategic agricultural conservation in Michigan's Saginaw Bay watershed	Fales, M; Dell, R; Herbert, ME; Sowa, SP; Asher, J; O'Neil, G; Doran, PJ; Wickerham, B	CE	conservation practice	US	Threat Abatement	0	1	1	0	0
Management strategies to mitigate the impacts of climate change on sea turtle's terrestrial reproductive phase	Fuentes, MMPB; Fish, MR; Maynard, JA	CE	academic	NA	Mixed Management	1	1	0	0	0
Managing and learning with multiple models: Objectives and optimization algorithms	Probert, WJM; Hauser, CE; McDonald-Madden, E; Runge, MC; Baxter, PWJ; Possingham, HP	AM	academic	Australia	Population Management	1	1	0	1	0
Managing invasive species in cities: a decision support framework applied to Cape Town	Gaertner, M; Novoa, A; Fried, J; Richardson, DM	AM	academic	South Africa	Threat Abatement	0	1	1	1	0

Managing multi-lateral, intergovernmental projects and programmes: the case of the UNEP/GEF South China Sea project	Pernetta, JC; Jiang, YH	AM	conservation practice	China	Management not specified	0	1	1	0	0
Managing successional trajectories in alien-dominated, novel ecosystems by facilitating seedling regeneration: A case study	Kueffer, C; Schumacher, E; Dietz, H; Fleischmann, K; Edwards, PJ	AM	academic	Seychelles	Restoration	1	1	0	1	0
Managing Urban Plant Invasions: a Multi-Criteria Prioritization Approach	Potgieter, LJ; Gaertner, M; Irlich, UM; O'Farrell, PJ; Stafford, L; Vogt, H; Richardson, DM	MCDA	academic	South Africa	Mixed Management	0	1	1	0	0
Marine conservation of multispecies and multi-use areas with various conservation objectives and targets	Schmiing, M; Diogo, H; Santos, RS; Afonso, P	SCP	academic	Azores	Spatial Prioritisation	1	1	1	1	0
Marine systematic conservation planning for Rodri	Pasnin, O; Attwood, C; Klaus, R"	SCP	academic	Mauritius	Spatial Prioritisation	1	0	1	1	0
Matches and mismatches between national and EU-wid	Kukkala, AS; Arponen, A; Maiorano, L; Moilanen, A	SCP	academic	Europe	Spatial Prioritisation	1	0	0	1	0
Mathematical problem definition for ecological res	McBride, MF; Wilson, KA; Burger, J; Fang, YC; Lul	SCP	academic	US	Mixed Management	1	0	1	0	0
Maximising return on conservation investment in th	Withey, JC; Lawler, JJ; Polasky, S; Plantinga, AJ	mixed	academic	US	Spatial Prioritisation	1	1	1	1	0
Maximizing Age-0 Spot Export from a South Carolina	Robinson, KF; Jennings, CA	SDM	conservation practice	US	Mixed Management	1	1	1	1	0
Maximizing species conservation in continental Ecu	Lessmann, J; Munoz, J; Bonaccorso, E"	SCP	academic	Ecuador	Spatial Prioritisation	1	1	0	1	0
MDPtoolbox: a multi-platform toolbox to solve stochastic dynamic programming problems	Chades, I; Chapron, G; Cros, MJ; Garcia, F; Sabbadin, R	SCP	academic	theoretical	Spatial Prioritisation	1	1	0	0	0
Measuring the effectiveness of regional conservati	Payet, K; Rouget, M; Lagabrielle, E; Esler, KJ"	SCP	academic	Reunion Island	Spatial Prioritisation	1	0	1	1	1
Minimum data requirements for designing a set of	Ban, NC"	SCP	academic	Canada	Spatial Prioritisation	1	0	1	1	0
Missing the Boat on Freshwater Fish Conservation i	Grantham, TE; Fesenmyer, KA; Peek, R; Holmes, E;	SCP	academic	US	Spatial Prioritisation	1	0	0	0	0
Model-based scenario planning to develop climate change adaptation strategies for rare plant populations in grassland reserves	Phillips-Mao, L; Galatowitsch, SM; Snyder, SA; Haight, RG	AM	academic	US	Restoration	0	1	0	1	0

Modeling with uncertain science: estimating mitigation credits from abating lead poisoning in Golden Eagles	Cochrane, JF; Lonsdorf, E; Allison, TD; Sanders-Reed, CA	AM	academic	US	Threat Abatement	1	1	0	1	0
Modelling decision-making regarding wetland services for wetland management in Tram Chim National Park, Vietnam	Nguyen, TTN; Evans, EA; Migliaccio, KW	MCDA	academic	Vietnam	Spatial Prioritisation	0	1	1	0	0
Modelling horse management in the Australian Alps	Beeton, NJ; Johnson, CN	CE	academic	Australia	Threat Abatement	0	1	1	1	0
Modelling tropical fire ant (Solenopsis geminata)	Baker, CM; Hodgson, JC; Tartaglia, E; Clarke, RH	mixed	conservation practice	Australia	Threat Abatement	0	1	1	1	0
Modelling with stakeholders to integrate biodivers	Lagabrielle, E; Botta, A; Dare, W; David, D; Aube	SCP	conservation practice	Mascarene archipelago	Spatial Prioritisation	1	1	1	1	1
Monitoring ecological consequences of efforts to restore landscape-scale connectivity	Watson, DM; Doerr, VAJ; Banks, SC; Driscoll, DA; van der Ree, R; Doerr, ED; Sunnucks, P	AM	conservation practice	Australia	Restoration	1	0	0	1	0
Multi-Action Planning for Threat Management: A Nov	Cattarino, L; Hermoso, V; Carwardine, J; Kennard,	SCP	academic	Australia	Threat Abatement	1	1	1	1	0
Multi-objective optimization in systematic conserv	Schlottfeldt, S; Walter, MEMT; Carvalho, ACPLF; S	SCP	academic	Brazil	Spatial Prioritisation	1	0	0	1	0
Multicriteria Decision Analysis of Stream Restoration: Potential and Examples	Corsair, HJ; Ruch, JB; Zheng, PQ; Hobbs, BF; Koonce, JF	MCDA	academic	US	Restoration	0	1	1	1	1
Multiple methods for multiple futures: Integrating qualitative scenario planning and quantitative simulation modeling for natural resource decision making	Symstad, AJ; Fisichelli, NA; Miller, BW; Rowland, E; Schuurman, GW	AM	conservation practice	US	Mixed Management	0	1	0	1	0
Multiple-species conservation planning for Europea	Jantke, K; Schneider, UA"	SCP	academic	Europe	Spatial Prioritisation	1	0	1	1	0
Multiscale Analysis of Restoration Priorities for Marine Shoreline Planning	Diefenderfer, HL; Sobocinski, KL; Thom, RM; May, CW; Borde, AB; Southard, SL; Vavrinec, J; Sather, NK	SCP	academic	US	Mixed Management	0	1	0	1	0
MULTISPECIES MODELING FOR ADAPTIVE MANAGEMENT OF HORSESHOE CRABS AND RED	McGowan, CP; Smith, DR; Sweka, JA; Martin, J; Nichols, JD; Wong, R; Lyons, JE;	AM	academic	US	Population Management	1	1	0	1	0

KNOTS IN THE DELAWARE BAY	Niles, LJ; Kalasz, K; Brust, J									
National parks as protected areas for US freshwate	Lawrence, DJ; Larson, ER; Liermann, CAR; Mims, MC	SCP	academic	US	Spatial Prioritisation	1	1	1	1	0
Nature conservation: priority-setting needs a glob	Freudenberger, L; Hobson, P; Schluck, M; Kreft, S	SCP	academic	global	Spatial Prioritisation	0	1	1	1	0
Navigating trade-offs in land-use planning: integr	Adams, VM; Pressey, RL; Stoeckl, N"	SCP	conservation practice	Australia	NA	1	1	1	1	1
Odense Pilot River Basin: implementation of the EU Water Framework Directive in a shallow eutrophic estuary (Odense Fjord, Denmark) and its upstream catchment	Petersen, JD; Rask, N; Madsen, HB; Jorgensen, OT; Petersen, SE; Nielsen, SVK; Pedersen, CB; Jensen, MH	CE	academic	Denmark	Threat Abatement	0	1	1	1	0
On the importance of taking into account agricultu	Herve, M; Albert, CH; Bondeau, A"	SCP	academic	France	Spatial Prioritisation	0	1	0	1	0
Optimal control of native predators	Martin, J; O'Connell, AF; Kendall, WL; Runge, MC;	mixed	conservation practice	US	Threat Abatement	1	1	0	1	0
Optimal dynamic control of invasions: applying a s	Adams, VM; Setterfield, SA"	SCP	academic	Australia	Spatial Prioritisation	1	1	1	1	0
Optimal timing for managed relocation of species faced with climate change	McDonald-Madden, E; Runge, MC; Possingham, HP; Martin, TG	AM	academic	theoretical	NA	1	1	0	1	0
Optimal water depth management on river-fed Nation	Nicol, S; Griffith, B; Austin, J; Hunter, CM	SDM	academic	US	NA	1	1	0	1	0
Optimized Spatial Priorities for Biodiversity Cons	Wu, RD; Long, YC; Malanson, GP; Garber, PA; Zhang	SCP	academic	China	Spatial Prioritisation	1	1	0	1	0
Optimizing disturbance management for wildlife pro	Dhanjal-Adams, KL; Mustin, K; Possingham, HP; Full	mixed	academic	Australia	Threat Abatement	1	1	1	1	1
Optimizing search strategies for invasive pests: learn before you leap	Baxter, PWJ; Possingham, HP	AM	academic	Australia	Threat Abatement	0	1	1	1	1
Options for Managing Hypoxic Blackwater in River Systems: Case Studies and Framework	Whitworth, KL; Kerr, JL; Mosley, LM; Conallin, J; Hardwick, L; Baldwin, DS	AM	academic	Australia	Threat Abatement	0	1	0	0	0
Participatory coastal management through elicitation of ecosystem service preferences and modelling driven	Martinez-Lopez, J; Teixeira, H; Morgado, M; Almagro, M; Sousa, AI; Villa, F; Balbi, S;	MCDA	academic	Portugal	Mixed Management	0	1	1	1	0

by "coastal squeeze"	Genua-Olmedo, A; Nogueira, AJA; Lillebo, AI									
Pelagic bioregionalisation using open-access data	Roberson, LA; Lagabrielle, E; Lombard, AT; Sink,	SCP	conservation practice	South Africa	Spatial Prioritisation	0	1	1	0	0
Planning for Implementation: Landscape-Level Resto	Thompson, BA"	SCP	conservation practice	US	Mixed Management	1	1	0	0	0
Planning for optimal conservation of geographical	Diniz, JAF; Melo, DB; de Oliveira, G; Collevatti,	SCP	academic	Brazil	Spatial Prioritisation	1	0	1	1	0
Planning impact avoidance and biodiversity offsett	Moilanen, A"	SCP	academic	Australia	Mixed Management	1	1	1	1	0
Planning Marine Reserve Networks for Both Feature	Bode, M; Williamson, DH; Weeks, R; Jones, GP; Alm	SCP	academic	Australia	Spatial Prioritisation	1	0	1	1	0
Planning priority conservation areas under climate	Qu, H; Wang, CJ; Zhang, ZX"	SCP	academic	China	Spatial Prioritisation	0	1	0	1	0
Planning protected areas network that are relevant	Vale, MM; Souza, TV; Alves, MAS; Crouzeilles, R"	SCP	academic	Brazil	Spatial Prioritisation	1	1	0	1	0
Population viability management: ecological standards to guide adaptive management for rare species	Bakker, VJ; Doak, DF	AM	conservation practice	US	Threat Abatement	1	1	0	1	0
Portfolio Decision Analysis Framework for Value-Focused Ecosystem Management	Convertino, M; Valverde, LJ	mixed	academic	US	Mixed Management	1	1	1	1	1
Practical applications of monitoring results to improve managing for coral reef resilience: a case study in the Mexican Caribbean	Ladd, MC; Collado-Vides, L	AM	academic	Mexico	Mixed Management	0	1	0	0	0
Predicting willingness-to-sell and its utility for	Guerrero, AM; Knight, AT; Grantham, HS; Cowling,	SCP	academic	South Africa	Spatial Prioritisation	1	1	1	1	1
Prioritising Invasive Species Control Actions: Evaluating Effectiveness, Costs, Willingness to Pay and Social Acceptance	Roberts, M; Cresswell, W; Hanley, N	CE	academic	Bonaire, Caribbean Netherlands	Threat Abatement	1	1	1	1	0
Prioritising Mangrove Ecosystem Services Results in Spatially Variable Management Priorities	Atkinson, SC; Jupiter, SD; Adams, VM; Ingram, JC; Narayan, S; Klein, CJ; Possingham, HP	CE	academic	Fiji	Mixed Management	1	1	1	1	1

Prioritizing Invasive Plant Management with Multi-Criteria Decision Analysis	Hohmann, MG; Just, MG; Frank, PJ; Wall, WA; Gray, JB	MCDA	academic	US	Mixed Management	1	1	1	1	0
Prioritizing rat eradication on islands by cost and effectiveness to protect nesting seabirds	Capizzi, D; Baccetti, N; Sposimo, P	CE	academic	Italy	Threat Abatement	1	1	1	1	0
Prioritizing Sites for Protection and Restoration	Braid, ACR; Nielsen, SE"	SCP	academic	Canada	Mixed Management	1	1	0	0	1
Prioritizing threat management for biodiversity conservation	Carwardine, J; O'Connor, T; Legge, S; Mackey, B; Possingham, HP; Martin, TG	CE	conservation practice	Australia	Threat Abatement	1	1	1	1	0
Priority areas for the conservation of perennial p	Zhang, MG; Slik, JWF; Ma, KP"	SCP	academic	China	Spatial Prioritisation	1	0	0	0	0
Priority threat management of invasive animals to protect biodiversity under climate change	Firn, J; Maggini, R; Chades, I; Nicol, S; Walters, B; Reeson, A; Martin, TG; Possingham, HP; Pichancourt, JB; Ponce-Reyes, R; Carwardine, J	mixed	academic	Australia	Threat Abatement	1	1	1	1	0
Proposed biodiversity conservation areas: gap ana	Li, RQ; Powers, R; Xu, M; Zheng, YP; Zhao, SJ"	SCP	academic	China	Spatial Prioritisation	1	0	1	0	0
Protected areas and spatial conservation prioriti	Nori, J; Torres, R; Lescano, JN; Cordier, JM; Per	SCP	academic	Bolivia, Paraguay, Argentina , Brazil	Spatial Prioritisation	1	1	0	1	0
Quantifying and resolving conservation conflicts i	Mazziotta, A; Podkopaev, D; Trivino, M; Miettinen	SCP	academic	Finland	NA	1	1	1	1	1
Quantifying ecosystem service trade-offs: The case of an urban floodplain in Vienna, Austria	Sanon, S; Hein, T; Douven, W; Winkler, P	MCDA	conservation practice	Austria	Restoration	1	1	1	1	1
Quantifying the expected value of uncertain management choices for over-abundant Greylag Geese	Tulloch, AIT; Nicol, S; Bunnefeld, N	AM	academic	Scotland	Population Management	1	1	1	1	0
Recent advances in applying decision science to ma	Marcot, BG; Thompson, MP; Runge, MC; Thompson, FR;	mixed	conservation practice	US	Threat Abatement	1	1	1	1	1
Recent advances in applying decision science to ma	Marcot, BG; Thompson, MP; Runge, MC; Thompson, FR;	mixed	conservation practice	US	Threat Abatement	1	1	1	0	1

Reducing Carryover Effects on the Migration and Spawning Success of Sockeye Salmon through a Management Experiment of Dam Flows	Burnett, NJ; Hinch, SG; Bett, NN; Braun, DC; Casselman, MT; Cooke, SJ; Gelchu, A; Lingard, S; Middleton, CT; Minke-Martin, V; White, CFH	AM	academic	Canada	Restoration	0	1	0	1	0
Reducing Reforestation Costs in Lebanon: Adaptive Field Trials	Haroutunian, G; Chojnacky, DC; El Riachy, R; Chojnacky, CC	mixed	conservation practice	Lebanon	Restoration	1	0	1	1	0
Reliable, verifiable and efficient monitoring of	Ji, YQ; Ashton, L; Pedley, SM; Edwards, DP; Tang,	SCP	academic	Malaysia	NA	1	1	1	1	0
Reorienting Systematic Conservation Assessment for	Sewall, BJ; Freestone, AL; Moutui, MFE; Toilibou,	SCP	conservation practice	Comoros	Spatial Prioritisation	0	1	1	1	1
Reptile species persistence under climate change a	Nori, J; Leynaud, GC; Volante, J; Abdala, CS; Scr	SCP	academic	Argentina	Spatial Prioritisation	0	0	0	1	0
Reserve network planning for fishes in the middle	Huang, XY; Li, F; Chen, JK"	SCP	academic	China	Spatial Prioritisation	1	1	0	0	0
Reserve selection and persistence: complementing t	Pinto, MP; Viveiros Grelle, CE"	SCP	academic	Brazil	Spatial Prioritisation	1	0	1	1	0
Reserves in Context: Planning for Leakage from Pro	Renwick, AR; Bode, M; Venter, O"	SCP	academic	Indonesia	Spatial Prioritisation	1	1	1	1	0
Resolving coastal conflicts using marine spatial planning	Tuda, AO; Stevens, TF; Rodwell, LD	MCDA	academic	Kenya	Spatial Prioritisation	1	1	1	1	0
Resolving future fire management conflicts using m	Driscoll, DA; Bode, M; Bradstock, RA; Keith, DA; P	MCDA	academic	Australia	Threat Abatement	1	1	1	1	1
Restoration planning to guide Aichi targets in a m	Tobon, W; Urquiza-Haas, T; Koleff, P; Schroter, M	mixed	academic	Mexico	Mixed Management	1	0	1	1	0
Restricted by borders: trade-offs in transboundary	Dolezsai, A; Saly, P; Takacs, P; Hermoso, V; Eros	SCP	academic	Hungary	Spatial Prioritisation	1	1	1	1	1
Revealing beliefs: using ensemble ecosystem modelling to extrapolate expert beliefs to novel ecological scenarios	Bode, M; Baker, CM; Benshemesh, J; Burnard, T; Rumpff, L; Hauser, CE; Lahoz-Monfort, JJ; Wintle, BA	AM	academic	Australia	Mixed Management	1	1	0	1	0
Scale-based freshwater conservation planning: tow	Rivers-Moore, NA; Goodman, PS; Nel, JL"	SCP	conservation practice	South Africa	Spatial Prioritisation	1	0	1	1	0
Science, Uncertainty, and Values in Ecological Res	Failing, L; Gregory, R; Higgins, P	mixed	conservation practice	Canada	Restoration	0	1	1	1	1
Selecting cost-effective areas for restoration of	Adame, MF; Hermoso, V; Perhans, K; Lovelock,	SCP	academic	Mexico	Restoration	1	1	1	1	0

ecosystem services	CE; Herrera-Silveira, JA									
Selection of invasive wild pig countermeasures using multicriteria decision analysis	Brondum, MC; Collier, ZA; Luke, CS; Goatcher, BL; Linkov, I	MCDA	academic	US	Threat Abatement	0	1	1	1	0
Selective-logging and oil palm: multitaxon impact	Edwards, DP; Magrach, A; Woodcock, P; Ji, YQ; Lim	SCP	academic	Borneo	Spatial Prioritisation	1	1	1	1	1
Setting conservation management thresholds using a novel participatory modeling approach	Addison, PFE; de Bie, K; Rumpff, L	SDM	conservation practice	Australia	Threat Abatement	1	1	1	1	1
Setting conservation priorities in cities: approa	Cimon-Morin, J; Poulin, M"	SCP	academic	Canada	Spatial Prioritisation	1	1	1	1	1
Shifting protected areas: scheduling spatial prior	Alagador, D; Cerdeira, JO; Araujo, MB"	SCP	academic	Spain, Portugal	Spatial Prioritisation	1	1	1	1	1
Simulating the effects of using different types of	Carvalho, SB; Brito, JC; Pressey, RL; Crespo, E;	SCP	academic	Portugal, Spain	Spatial Prioritisation	1	0	1	1	0
Simulating the value of collaboration in multi-act	Gordon, A; Bastin, L; Langford, WT; Lechner, AM;	SCP	academic	NA	Spatial Prioritisation	1	0	1	1	0
Site complementarity between biodiversity and ecos	Cimon-Morin, J; Darveau, M; Poulin, M"	SCP	academic	Canada	Spatial Prioritisation	1	0	1	1	0
Small mammals and retention islands: An experimental study of animal response to alternative logging practices	Lindenmayer, DB; Knight, E; McBurney, L; Michael, D; Banks, SC	AM	academic	Australia	Threat Abatement	0	1	0	1	0
Solving conservation planning problems with intege	Beyer, HL; Dujardin, Y; Watts, ME; Possingham, HP	SCP	academic	NA	Spatial Prioritisation	1	0	1	1	1
Spatial characteristics of species distributions a	Kujala, H; Moilanen, A; Gordon, A"	SCP	academic	Australia, Finland	Spatial Prioritisation	1	0	0	1	0
Spatial conservation priorities for top predators	Sobral, FL; Jardim, L; Lemes, P; Machado, N; Loyo	SCP	academic	Brazil	Spatial Prioritisation	1	0	0	1	1
Spatial conservation prioritization of biodiversit	Carvalho, SB; Velo-Anton, G; Tarroso, P; Portela,	SCP	academic	Spain, Portugal	Spatial Prioritisation	1	0	1	1	0
Spatial Education: Improving Conservation Delivery	Moore, CT; Shaffer, TL; Gannon, JJ	mixed	conservation practice	US	Restoration	1	1	1	1	0
Spatial MCDA in marine planning: Experiences from the Mediterranean and Baltic Seas	Tammi, I; Kalliola, R	MCDA	academic	Greece	Mixed Management	0	1	1	1	0
Spatial prioritization of	Moilanen, A; Leathwick,	SCP	academic	New Zealand	Mixed Management	1	1	1	1	1

conservation management	JR; Quinn, JM"									
Spatial, socio-economic, and ecological implicati	Metcalfe, K; Vaughan, G; Vaz, S; Smith, RJ"	SCP	academic	UK	Spatial Prioritisation	1	0	1	1	1
Species distributions represent intraspecific gene	Hermoso, V; Kennard, MJ; Schmidt, DJ; Bond, N; Hu	SCP	academic	Australia	Spatial Prioritisation	1	1	1	1	0
Species specific connectivity in reserve-network d	Cerdeira, JO; Pinto, LS; Cabeza, M; Gaston, KJ"	SCP	academic	NA	Spatial Prioritisation	1	1	0	1	0
Staged-scale restoration: Refining adaptive management to improve restoration effectiveness	Bakker, JD; Delvin, EG; Dunwiddie, PW	AM	conservation practice	US	Restoration	1	1	0	1	0
Stakeholder Engagement and Knowledge Co-Creation in Water Planning: Can Public Participation Increase Cost-Effectiveness?	Graversgaard, M; Jacobsen, BH; Kjeldsen, C; Dalgaard, T	CE	conservation practice	Denmark	Restoration	1	0	1	0	0
State-and-transition modelling for Adaptive Management of native woodlands	Rumpff, L; Duncan, DH; Vesk, PA; Keith, DA; Wintle, BA	mixed	academic	Australia	Mixed Management	1	1	1	1	0
State-Dependent Resource Harvesting with Lagged Information about System States	Johnson, FA; Fackler, PL; Boomer, GS; Zimmerman, GS; Williams, BK; Nichols, JD; Dorazio, RM	AM	academic	US	Population Management	1	1	1	1	0
State-space modeling to support management of brucellosis in the Yellowstone bison population	Hobbs, NT; Geremia, C; Treanor, J; Wallen, R; White, PJ; Hooten, MB; Rhyan, JC	AM	academic	US	Population Management	1	1	0	1	1
Strategic Grassland Bird Conservation throughout t	Drum, RG; Ribic, CA; Koch, K; Lonsdorf, E; Grant,	SDM	academic	US, Canada	Mixed Management	1	1	1	1	0
Structured decision making as a conceptual framework to identify thresholds for conservation and management	Martin, J; Runge, MC; Nichols, JD; Lubow, BC; Kendall, WL	mixed	academic	theoretical	Threat Abatement	1	1	1	1	0
Structured decision making as a conservation tool	O'Donnell, KM; Messerman, AF; Barichivich, WJ; Sem	mixed	conservation practice	US	Mixed Management	1	1	1	1	0
Structured decision making as a conservation tool for recovery planning of two endangered salamanders	O'Donnell, KM; Messerman, AF; Barichivich, WJ; Sem	mixed	conservation practice	US	Restoration	1	1	1	1	0
Structured decision making as a framework for large-scale wildlife harvest	Robinson, KF; Fuller, AK; Hurst, JE; Swift, BL; Kirsch, A; Farquhar, J;	SDM	conservation practice	US	Population Management	1	1	1	1	1

management decisions	Decker, DJ; Siemer, WF									
Structured decision making as a proactive approach to dealing with sea level rise in Florida	Martin, J; Fackler, PL; Nichols, JD; Lubow, BC; Eaton, MJ; Runge, MC; Stith, BM; Langtimm, CA	mixed	academic	US	Threat Abatement	1	1	1	1	0
Structured decision making for managing pneumonia	Sells, SN; Mitchell, MS; Edwards, VL; Gude, JA; An	SDM	conservation practice	US	Population Management	1	1	1	1	1
Structured Decision-Making and Rapid Prototyping to Plan a Management Response to an Invasive Species	Blomquist, SM; Johnson, TD; Smith, DR; Call, GP; Miller, BN; Thurman, WM; McFadden, JE; Parkin, MJ; Boomer, GS	mixed	conservation practice	US	Mixed Management	1	1	1	1	1
Sympathy for the Devil: Detailing the Effects of	Cheok, J; Pressey, RL; Weeks, R; Andrefouet, S; M	SCP	academic	Fiji, Micronesi a	Spatial Prioritisation	1	0	1	1	0
Systematic conservation assessment for the Mesoam	Sarkar, S; Sanchez-Cordero, V; Londono, MC; Fulle	SCP	academic	10 countries Mesoame rica: see comment box	Spatial Prioritisation	1	0	0	1	0
Systematic Conservation Planning for Groundwater E	Asmyhr, MG; Linke, S; Hose, G; Nipperess, DA"	SCP	academic	Australia	Spatial Prioritisation	1	0	1	1	0
Systematic conservation planning in floodplain fis	Chiaravalloti , RM"	SCP	academic	Brazil	Spatial Prioritisation	1	0	1	1	0
Systematic conservation planning in the eastern En	Delavenne, J; Metcalfe, K; Smith, RJ; Vaz, S; Mar	SCP	academic	UK, France	Spatial Prioritisation	1	0	1	1	1
Systematic Conservation Planning in the Face of Cl	Schloss, CA; Lawler, JJ; Larson, ER; Papendick, H	SCP	academic	US	Mixed Management	1	1	1	1	1
Systematic conservation planning in the Mediterran	Maiorano, L; Bartolino, V; Colloca, F; Abella, A;	SCP	academic	Italy	Spatial Prioritisation	1	1	1	1	0
Systematic site selection for multispecies monitor	Carvalho, SB; Goncalves, J; Guisan, A; Honrado, J	SCP	academic	Portugal	Spatial Prioritisation	1	0	1	1	1
Systematically designating conservation areas for	Lin, YP; Lin, WC; Wang, YC; Lien, WY; Huang, T; H	SCP	academic	Taiwan	Spatial Prioritisation	1	1	1	1	0
Targeting areas for Reducing Emissions from Deforestation and forest Degradation (REDD+) projects in Tanzania	Lin, LW; Sills, E; Cheshire, H	MCDA	academic	Tanzania	Spatial Prioritisation	1	1	1	1	0
Targeting climate diversity in	Heller, NE; Kreitler, J;	SCP	academic	US	Spatial Prioritisation	1	1	1	1	0

conservation planni	Ackerly, DD; Weiss, SB;									
Targeting Global Protected Area Expansion for Impe	Venter, O; Fuller, RA; Segan, DB; Carwardine, J;	SCP	academic	global	Spatial Prioritisation	1	0	1	1	1
The Biodiversity Forecasting Toolkit: Answering t	Drielsma, M; Ferrier, S; Howling, G; Manion, G; T	SCP	academic	Australia	Mixed Management	1	1	0	1	0
The effect of target setting on conservation in Ca	Wiersma, YF; Sleep, DJH"	SCP	academic	Canada	Spatial Prioritisation	1	0	1	1	0
The efficacy of combined educational and site management actions in reducing off-trail hiking in an urban-proximate protected area	Hockett, KS; Marion, JL; Leung, YF	AM	conservation practice	US	Mixed Management	0	1	1	1	0
The Grain of Spatially Referenced Economic Cost an	Sutton, NJ; Armsworth, PR"	SCP	academic	US	Spatial Prioritisation	1	0	1	1	0
The influence of planning unit characteristics on	Nhancale, BA; Smith, RJ"	SCP	academic	South Africa, Mozambi que, Swaziland	Spatial Prioritisation	1	1	1	1	0
The plans they are a-changin': More frequent itera	Cheok, J; Pressey, RL; Weeks, R; VanderWal, J; St	SCP	academic	Fiji	Spatial Prioritisation	1	0	1	1	0
The role of scale in designing protected area syst	Kendall, BE; Klein, CJ; Possingham, HP"	SCP	academic	Africa	Spatial Prioritisation	1	0	1	1	0
The sensitivity of gap analysis to conservation ta	Vimal, R; Rodrigues, ASL; Mathevet, R; Thompson,	SCP	academic	France	Spatial Prioritisation	1	0	0	1	0
The Value of Using Feasibility Models in Systemati	Tulloch, AIT; Tulloch, VJD; Evans, MC; Mills, M"	SCP	academic	Australia	Mixed Management	1	1	1	1	1
To exclose nests or not: structured decision making for the conservation of a threatened species	Cohen, JB; Hecht, A; Robinson, KF; Osnas, EE; Tyre, AJ; Davis, C; Kocek, A; Maslo, B; Melvin, SM	SDM	academic	US	Population Management	1	1	0	1	1
Toward a Conceptual Framework for Blending Social	Pasquini, L; Twyman, C; Wainwright, J"	SCP	academic	South Africa	Spatial Prioritisation	0	0	1	0	0
Toward adaptive management of coastal MPAs: The influence of different conservation targets and costs on the design of no-take areas	Abecasis, D; Afonso, P; Erzini, K	mixed	academic	Portugal	Spatial Prioritisation	1	1	1	1	0
Towards a systematic conservation plan for the Ara	Holness, S; Knight, M; Sorensen, M; Ramadan, Y; O	SCP	academic	Arabic Peninsula	Spatial Prioritisation	1	0	1	0	0
Towards strategic offsetting of biodiversity loss	Kujala, H; Whitehead, AL; Morris, WK; Wintle, BA"	SCP	academic	Australia	Mixed Management	1	1	1	1	1

Trade-off analysis of ecosystem service provision in nature networks	Vogdrup-Schmidt, M; Strange, N; Olsen, SB; Thorsen, BJ	MCDA	academic	Denmark	Mixed Management	1	0	1	1	1
Trade-offs in carbon storage and biodiversity cons	Reside, AE; VanDerWal, J; Moran, C"	SCP	academic	Australia	Spatial Prioritisation	0	1	1	1	1
Two-step adaptive management for choosing between two management actions	Moore, AL; Walker, L; Runge, MC; McDonald-Maden, E; McCarthy, MA	AM	academic	New Zealand	Population Management	1	0	1	1	1
Uncertainty, Robustness, and the Value of Information in Managing a Population of Northern Bobwhites	Johnson, FA; Hagan, G; Palmer, WE; Kemmerer, M	AM	conservation practice	US	Mixed Management	1	1	1	1	0
Understanding and Finding Solutions to the Problem	van der Burg, MP; Jenni, KE; Nieman, TL; Eash, JD;	SDM	conservation practice	US	Threat Abatement	1	1	1	0	0
Understanding the effects of different social data	Karimi, A; Tulloch, AIT; Brown, G; Hockings, M"	SCP	academic	Australia	Spatial Prioritisation	0	0	1	1	1
Use of decision analysis interviews to support the sustainable use of the forests in Finnish Upper Lapland	Mustajoki, J; Saarikoski, H; Marttunen, M; Ahtikoski, A; Hallikainen, V; Helle, T; Hypponen, M; Jokinen, M; Naskali, A; Tuulentie, S; Varmola, M; Vatanen, E; Ylisirnio, AL	MCDA	conservation practice	Finland	Mixed Management	0	1	1	1	0
Use of Inverse Spatial Conservation Prioritization	Kareksela, S; Moilanen, A; Tuominen, S; Kotiaho,	SCP	conservation practice	Finland	Spatial Prioritisation	1	1	1	1	1
Use of optimization algorithms to prioritize prote	Mehri, A; Salmanmahiny, A; Mirkarimi, SH; Rezaei,	SCP	academic	Iran	Spatial Prioritisation	1	0	1	1	0
Use of Structured Decision Making to Identify Monitoring Variables and Management Priorities for Salt Marsh Ecosystems	Neckles, HA; Lyons, JE; Guntenspergen, GR; Shriver, WG; Adamowicz, SC	mixed	conservation practice	US	Mixed Management	1	1	1	1	1
Use of structured decision-making to explicitly incorporate environmental process understanding in management of coastal restoration projects: Case study on barrier islands of the northern Gulf of Mexico	Dalyander, PS; Meyers, M; Mattsson, B; Steyer, G; Godsey, E; McDonald, J; Byrnes, M; Ford, M	SDM	conservation practice	US	Restoration	1	1	1	1	1
Using Bayesian Population Viability Analysis	Green, AW; Bailey, LL	AM	academic	US	Restoration	1	1	1	1	1

to Define Relevant Conservation Objectives										
Using counterfactuals to evaluate the cost-effectiveness of controlling biological invasions	McConnachie, MM; van Wilgen, BW; Ferraro, PJ; Forsyth, AT; Richardson, DM; Gaertner, M; Cowling, RM	mixed	academic	South Africa	Threat Abatement	0	1	1	1	0
Using globally threatened pelagic birds to identif	Dias, MP; Oppel, S; Bond, AL; Carneiro, APB; Cuth	SCP	academic	Tristan da Cunha archipelago	Spatial Prioritisation	1	1	1	1	0
Using modeling tools for implementing feasible lan	Fernandes, JP; Freire, M; Guiomar, N; Gil, A"	SCP	academic	Portugal	Mixed Management	1	0	1	1	0
Using multi-species occupancy models in structured	Sauer, JR; Blank, PJ; Zipkin, EF; Fallon, JE; Fall	SDM	conservation practice	US	NA	0	1	0	1	0
Using multivariate statistics to explore trade-off	Harris, LR; Watts, ME; Nel, R; Schoeman, DS; Poss	SCP	academic	South Africa	Spatial Prioritisation	1	1	1	1	1
Using Optimal Land-Use Scenarios to Assess Trade-	Adams, VM; Pressey, RL; Alvarez-Romero, JG"	SCP	conservation practice	Australia	Spatial Prioritisation	1	1	1	1	1
Using river-scale experiments to inform variable releases from large dams: a case study of emergent adaptive management	Watts, RJ; Ryder, DS; Allan, C; Commens, S	AM	conservation practice	Australia	Restoration	0	1	0	1	0
Using Short-Term Monitoring Data to Achieve Goals in a Large-Scale Restoration	Hagen, D; Evju, M	AM	conservation practice	Norway	Restoration	0	0	0	1	0
Using simulation modeling to inform management of invasive species: A case study of eastern brook trout suppression and eradication	Day, CC; Landguth, EL; Bearlin, A; Holden, ZA; Whiteley, AR	AM	academic	US	Threat Abatement	0	1	0	1	0
Using species distribution modeling to improve co	Zhang, MG; Zhou, ZK; Chen, WY; Slik, JWF; Cannon,	SCP	academic	China	Spatial Prioritisation	1	1	0	0	0
Using stochastic multi-criteria acceptability analysis methods in SEA: an application to the Park of Trasimeno (Italy)	Rocchi, L	MCDA	conservation practice	Italy	Spatial Prioritisation	0	1	1	1	0
Using Strategic Adaptive Management to Facilitate Implementation of Environmental Flow Programs in Complex Social-Ecological Systems	Conallin, J; Campbell, J; Baumgartner, L	AM	conservation practice	Australia	Restoration	1	1	0	0	0
Using Structured Decision Making to Help Implement	Gregory, R; Long, G	SDM	conservation practice	Canada	Mixed Management	1	1	1	1	1

Using Structured Decision Making to Manage Disease	Mitchell, MS; Gude, JA; Anderson, NJ; Ramsey, JM;	SDM	conservation practice	US	Population Management	1	1	1	1	1
Using the Bayesian Network Relative Risk Model Risk Assessment Process to Evaluate Management Alternatives for the South River and Upper Shenandoah River, Virginia	Johns, AF; Graham, SE; Harris, MJ; Markiewicz, AJ; Stinson, JM; Landis, WG	AM	academic	US	Threat Abatement	0	1	1	1	0
Using threat maps for cost-effective prioritization of actions to conserve coastal habitats	Giakoumi, S; Brown, CJ; Katsanevakis, S; Saunders, MI; Possingham, HP	CE	academic	Greece	Restoration	1	1	1	1	0
Value of adaptation in water protection - Economic impacts of uncertain climate change in the Baltic Sea	Ahlvik, L; Hyytiainen, K	AM	academic	Baltic Sea	Threat Abatement	0	1	1	1	0
Value-based ecosystem service trade-offs in multi-objective management in European mountain forests	Langner, A; Irauschek, F; Perez, S; Pardos, M; Zlatanov, T; Ohman, K; Nordstrom, EM; Lexer, MJ	MCDA	academic	Spain, Austria, Bulgaria	NA	0	0	1	1	1
Variable retention silviculture in Tasmania's wet forests: ecological rationale, adaptive management and synthesis of biodiversity benefits	Baker, SC; Read, SM	AM	conservation practice	Australia	Threat Abatement	0	1	0	1	0
Vital sites and actions: an integrated framework f	Overton, JM; Walker, S; Price, R; Stephens, RTT;	SCP	academic	New Zealand	Threat Abatement	1	1	0	0	0
Waiting can be an optimal conservation strategy,	Iacona, GD; Possingham, HP; Bode, M"	SCP	academic	Australia, Paraguay	Mixed Management	1	1	1	1	1
When do conservation planning methods deliver? Qua	Langford, WT; Gordon, A; Bastin, L"	SCP	academic	NA	Spatial Prioritisation	1	0	1	1	0
When do conservation planning methods deliver? Qua	Langford, WT; Gordon, A; Bastin, L"	SCP	academic	Australia	Spatial Prioritisation	1	0	1	1	0
When do we need more data? A primer on calculating the value of information for applied ecologists	Canessa, S; Guillera-Arroita, G; Lahoz-Monfort, JJ; Southwell, DM; Armstrong, DP; Chades, I; Lacy, RC; Converse, SJ	AM	academic	Italy	Population Management	1	0	0	1	0

When do we need more data? A primer on calculating the value of information for applied ecologists	Canessa, S; Guillera-Arroita, G; Lahoz-Monfort, JJ; Southwell, DM; Armstrong, DP; Chades, I; Lacy, RC; Converse, SJ	AM	academic	theoretical	Mixed Management	1	1	0	1	0
When experts disagree (and better science won't he	Gregory, R; Long, G; Colligan, M; Geiger, JG; Lase	mixed	conservation practice	US	Mixed Management	1	1	1	1	0
Which species, how many, and from where: Integrating habitat suitability, population genomics, and abundance estimates into species reintroduction planning	Malone, EW; Perkin, JS; Leckie, BM; Kulp, MA; Hurt, CR; Walker, DM	MCDA	academic	US	Mixed Management	1	0	0	1	1
Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program	Runge, MC; Converse, SJ; Lyons, JE	mixed	Conservation practice	US	Mixed Management	1	1	0	1	1
Zoning of Hangzhou Bay ecological red line using GIS-based multi-criteria decision analysis	Wang, CY; Delu, P	MCDA	academic	China	Spatial Prioritisation	0	1	1	1	0

Appendix III: Supplementary Materials for chapter 4

Supplementary material S4.1: changes made after pilot

Table S3. 1: Changes made after the pilot phase to the coding scheme.

Variable	Pilot categories	Updated categories	Reason
Applied conservation / academic	Implemented Suggested academic	Implemented Suggested Scientific applied Scientific theoretical	Applied academic studies were often categorized as implemented, because academic was linked to theoretical
Spatial scale	State/county level	Scrapped	Too often unclear if locations were truly rolled out over the whole state/county, better to classify as local or regional
Threat		Some explanation for land use change, human use, harvest and system medication added	Confusion about difference of harvest and system change for e.g. water extraction for irrigation, and if this fits to agriculture, harvest or system change
Realm	Terrestrial, marine, freshwater and combinations	Option added for “not mentioned”	To make clearer if entry was forgotten or decided to be NA
Type environmental/ economic/social/other objective	Codes 1 -5	Added : 6: increase	Seemed to be too frequent to be “other”

The variable related to implementation was collapsed to “applied conservation” and “academic” and the biodiversity related variable was further collapsed in studies that used the dataset, because of low agreement in the intermediate categories (Beher, Treml, and Wintle 2024 ,Beher et al 2024, in prep, equivalent to chapter 2 and 3 in this thesis).

Supplementary material S4.2: calculations for figures

Figure 4.1: average of 4 pairs: TRUE / FALSE entries between each additional rater compared to main rater for 21 examples for each variable, before and after discussion:

Each rater has the same (TRUE) or different (FALSE) entry in each of the 21 examples for each variable, which is expressed as value between 0 and 21 in column T_F. In a dataframe with columns *rater, variable, before/after, T_F*. Percent agreement is calculated in line 68 in code: fig1_comb$pp <- 100/21 * fig1_comb$T_F

Figure 4.2:

a): all pairwise comparison (each additional rater vs main rater) averaged for each variable. Line 113 in code (sum of all TRUE entries for each rater and each variable, then take average across 5 raters for each variable)

Rare: variables were coded with “FALSE” more than 50% (>52 out of 105)

frequent: variables were coded with “FALSE” less than 20% (< 21 out of 105)

b) all variables averaged for each rater

line 147 in code: (sum of all TRUE entries for each rater and each variable, then take average across all variables for each rater)

Figure 4.3,4.4,4.5: kappa and percent agreement with irr package: all combinations of groups between 1-4 additional raters – maybe Steve can check code and we need to discuss the difference between calculating agreement in random groups vs. agreement in a comparison of people/groups with main rater? The first aims at reproducibility, the second at validity/quality of codes the main rater produced?

Supplementary material S4.3: agreement with main rater before and after discussion rounds

Figure S3. 1: average agreement across all pairs of additional raters compared to the main rater, before and after each of the 6 rounds of group discussions. Discussed examples were n= 1 during the first discussion, and between 3-5 in all other discussions.

Supplementary material S4.4: comparison of different metrics

Table S3. 2: Metrics for agreement: kappa for individual raters and all raters, alpha for all raters, and percent agreement before and after discussion. The percent agreement after discussion differs drastically for some variables from kappa or alpha.

variable	kappa R1	kappa R2	kappa R3	kappa R4	kappa all	alpha all	pp before	pp after
count actions	0.2	0.2	0.3	0.1	0.3	0.3	14.3	81.0
continent	0.9	0.8	1.0	1.0	0.9	0.9	85.7	95.2
cost	0.6	0.6	0.5	0.7	0.6	0.6	57.1	85.7
count objectives	-0.1	0.2	0.1	0.1	0.2	0.2	4.8	85.7
country	0.8	0.9	0.9	0.8	0.8	0.8	71.4	100.0
economic objective	0.6	0.5	0.4	0.7	0.5	0.5	57.1	90.5
environmental objective	0.4	0.1	0.7	0.7	0.3	0.3	52.4	100.0
feasibility	0.3	0.1	0.3	0.0	0.2	0.2	14.3	95.2
implementation	0.1	0.6	0.6	0.5	0.4	0.4	57.1	90.5
socioeconomic obj	0.6	0.6	0.3	0.8	0.5	0.5	52.4	95.2
other objective	-0.1	0.0	-0.1	0.0	0.0	0.0	85.7	100.0
primary framework	0.8	0.8	0.8	0.8	0.8	0.8	57.1	100.0
sensitivity presence	0.1	0.1	0.2	0.0	0.1	0.1	4.8	57.1
sensitivity	0.5	0.6	0.8	0.8	0.5	0.5	66.7	100.0
social objective	0.1	0.3	0.2	0.3	0.4	0.4	38.1	71.4
spatial scale	0.3	0.4	0.5	0.5	0.4	0.4	19.0	66.7
biodiversity	0.5	0.8	0.5	0.5	0.6	0.6	57.1	85.7
realm	0.4	0.3	0.4	0.5	0.4	0.4	33.3	81.0
threat	0.4	0.2	0.3	0.3	0.3	0.3	28.6	90.5
threat presence	0.3	0.4	0.8	0.6	0.5	0.5	33.3	85.7
tradeoff	0.2	0.5	0.0	0.4	0.3	0.3	23.8	81.0
management	0.7	0.3	0.9	0.9	0.6	0.6	76.2	95.2
socioeconomic objective	0.2	-0.2	0.3	0.1	0.2	0.2	47.6	100.0

Appendix IV: Supplementary Materials for chapter 5

Supplementary material S5.1 Summary statistics and details of impact metrics

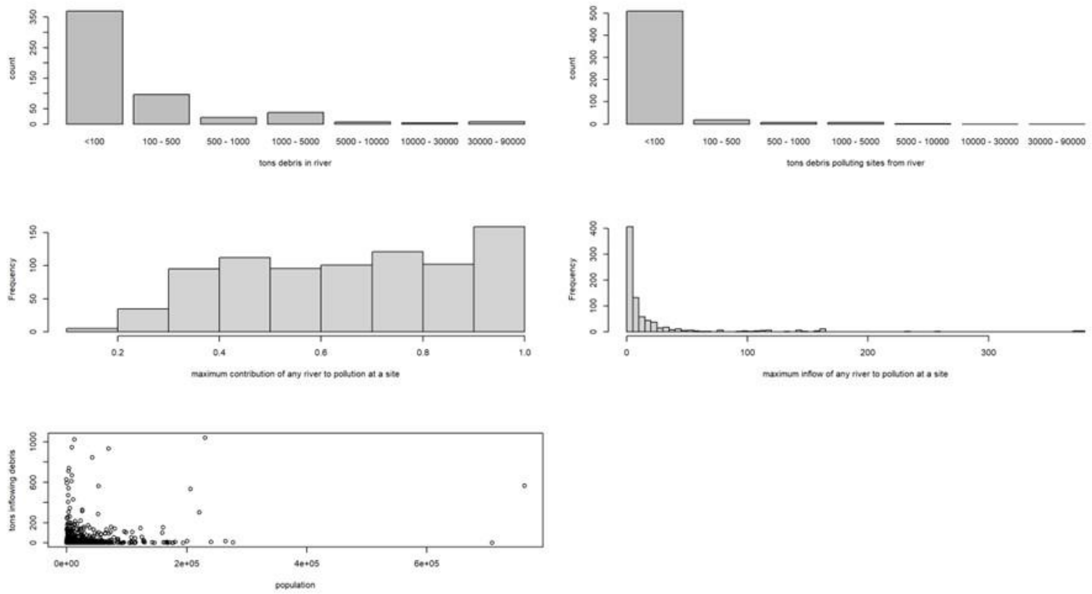

Figure S4. 1: Summary statistics for all impact metrics. Panel A shows a histogram of volume in each river (Eq4), panel B a histogram of total downstream pollution (Eq3), panel C the volumetric impact at receiving sites (Eq2), panel D the relative impact at receiving sites (Eq1), and panel E the correlation between inflowing debris and population density at the receiving site.

Details on calculating general impact metrics

1. [t] Impact at source river:

   Eq_4: Source river pollution [t] = load of plastic debris of source $river_i$

2. [t] Downstream impact across all sites:

   Eq_3: Impact across all receiving sites [t] = Σ inflow from source $river_i$ across all receiving $sites_{j:n}$:

3. [%] Fraction of the river load that pollutes sites across system:

   100 / eq4 * eq3

4. [n] Sites impacted by this source:

Count of receiving sites for each source locations in adjacency matrix

5. [km²] Area impacted (across all sites):

   Sum of area in shapefile with selected site IDs from general metric 4.

6. [n] Sites this source is the main source of pollution:

   Frequency of source locations linked to the maximum value at each receiving site based on adjacency matrices

Details on calculating environmental impact metrics

1. t] Volumetric impact downstream, see Eq2 in section 2.4:

   Eq_2: Impact receiving site [t] = inflow from $river_i$ at receiving $site_j$

2. [%] Reduction in pollution across sites & area:

   Eq_1: Relative impact receiving site [%] = inflow from $river_i$ at receiving $site_j$ / total inflow from all $rivers_{i:n}$ at receiving $site_j$ *100

3. [n] Sites with reduced pollution:

   General metric 4 split for different habitat types

4. [km²] Area with reduced pollution:

   General metric 5 split for different habitat types

Details on calculating social impact metrics

1. [n] Impact of a river on number of people within 8 km² vicinity:

   Select ID of all receiving sites for each source location and sum up population zonal statistics linked to these IDs

2. [n] River as main source of pollution for number of people within 8 km²
vicinity:

Select ID of all receiving sites and sum up population zonal statistics, but only for IDs of main sources

Details on calculating feasibility related impact metrics

1. [n] Technical feasibility: number of source rivers with large contribution to site pollution, width of estuary:

   Filter source locations in connectivity matrix above a certain percent contribution to inflow of debris at individual destination sites from connectivity matrix

2. [n] Political feasibility: number of EEZ impacted:

   Count intersecting EEZ polygons in EEZ with selection of endpoints of trajectories from each river in GIS software

Supplementary material S5.2 Parallel ranking of source rivers for all metrics

The parallel ranking (Table S5.1) reveals that rivers contributing the largest fraction of the pollution that impacts downstream sites (ranking highest for total downstream impact across all receiving sites, Table S5.1, column 3) did not rank high for other objectives. However, several rivers ranking high for high pollution at individual downstream sites (columns 7,9 and 11) also ranked high for multiple other objectives. Many of the 30 rivers carrying the highest volume of plastic debris impacted a large number of sites to a lesser degree but were not the main contributor of inflow for any of the most polluted sites (Tables S5.1 & S5.2). The rivers that carry a high load and also rank high for environmental or social impact can be further evaluated by comparing the different metrics on type and magnitude of impact to enable better judgment on the relative difference between the ranks (Table S5.2). The selection of options to compare in more detail is to a certain degree subjective and depends on the values of the decision makers and the weight they want to give to specific objectives. For example, river #255 ranks only high for 6 out of 12 objectives, but if coral reefs seem to be of high value, the most important pollution source should be included in the more detailed assessment. River #298 is an example of a source that ranks high for many objectives and is not included for further detailed analysis because it appears consistently in lower ranks than rivers Song Hau (#95) and Irrawaddy (#29).

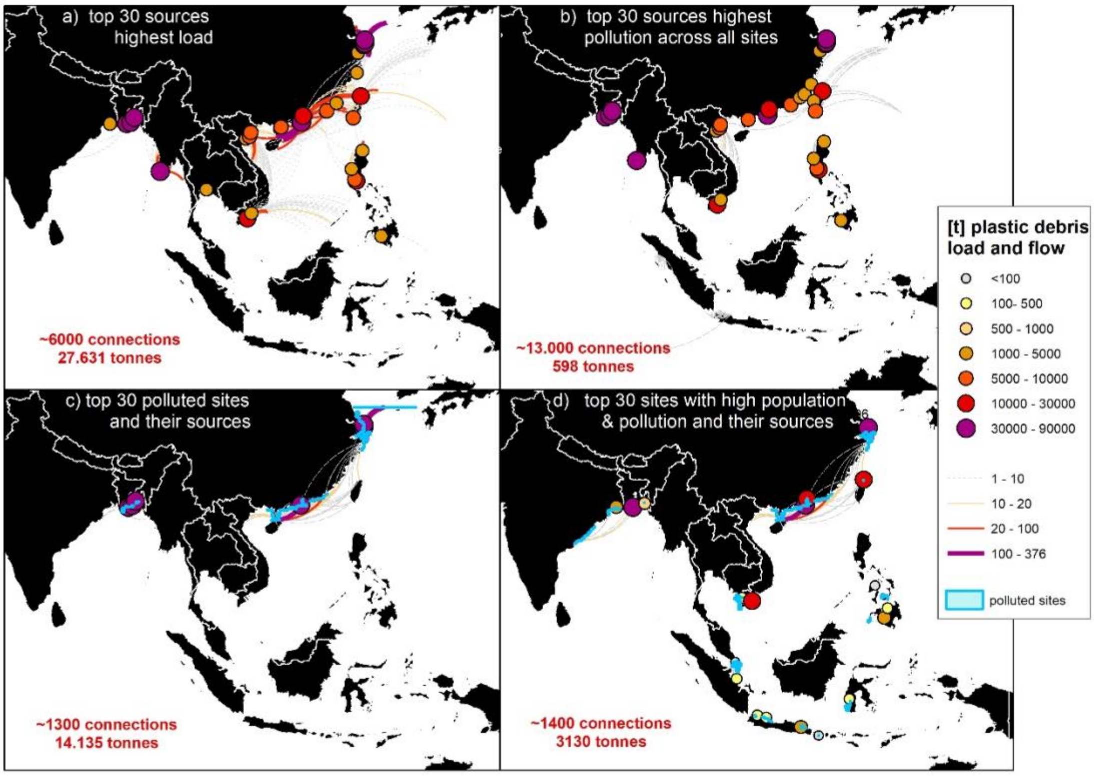

Figure S4. 2: Top 30 sources of plastic debris from ranking for different objectives, with connections to downstream receiving sites. Volume at source (a), top sources regarding total downstream impact in volume across all sites (b), top sources regarding highest volumetric impact at the most polluted downstream sites (c), top sources regarding volumetric impact at most polluted downstream sites relative to population density (d).

Table S4. 1: Parallel ranking of river IDs for multiple objectives and metrics, enabling the identification of clean-up locations that would benefit multiple objectives. Each column shows the top 30 source river IDs for one metric, ranked from 1-30. Blue fields in heading highlight social objectives, green fields environmental objectives. Color code highlights the number of co-benefits, with darker colors for river IDs that rank high for several metrics. Bold text = high ranks for 8 out of 12 metrics, light green fields = high ranks for 9 out of 12 metrics, medium green fields = high ranks for 10 out of 12 metrics, dark green fields = high ranks for 11 out of 12 metrics. River 255 ranks only for 6 objectives but is the most important source of pollution for coral reefs.

Rank	1: Eq$_1$: relative impact on downstream site [%]	2: Eq2: volumetric impact on downstream site [t]	3: Eq$_3$: total downstream impact across all sites [t]	4: Eq$_4$: impact at source / load in river [t]	5: Eq$_{2a}$: volumetric impact on downstream site [t], discounted for population	6: Eq$_{1a}$: relative impact on downstream site [%] discounted for population	7: Eq$_{2b}$: volumetric impact on most polluted downstream reefs	8: Eq$_{2b}$: volumetric impact on all downstream reefs	9: Eq$_{2c}$: volumetric impact on most polluted downstream Marine Protected Area	10: Eq$_{2c}$: volumetric impact on all downstream Marine Protected Areas	11: Eq$_{2d}$: volumetric impact on most polluted downstream Key Biodiversity Area	12: Eq$_{2d}$: volumetric impact on all downstream Key Biodiversity Areas
1	243	195	**196**	195	**146**	**146**	255	255	**197**	**197**	195	16
2	273	**196**	**197**	**196**	**196**	**196**	**146**	**146**	**15**	**15**	**196**	17
3	278	**197**	195	**197**	195	195	298	298	**196**	**196**	16	195
4	76	**146**	**146**	**146**	**197**	**197**	95	95	**146**	**146**	17	**196**
5	288	16	**15**	**15**	149	149	**126**	29	**123**	**123**	**15**	**15**
6	541	17	255	16	255	255	29	323	122	95	29	29
7	311	**15**	16	17	17	17	174	**126**	95	122	**208**	241
8	384	29	29	29	**208**	**208**	25	507	**126**	**126**	241	**208**
9	471	255	17	255	95	95	78	373	88	88	**223**	31
10	245	149	208	149	16	16	447	174	298	298	31	**223**
11	531	95	**123**	95	**15**	**15**	27	25	87	87	99	368
12	330	**208**	126	**208**	**123**	**123**	373	27	**208**	447	162	99
13	29	**123**	95	**123**	162	162	507	78	263	353	447	447
14	329	140	162	140	**223**	**223**	442	447	282	507	368	162
15	247	**126**	149	**126**	9	9	323	442	447	**208**	183	**197**
16	177	162	223	162	80	80	380	243	507	90	174	174
17	284	257	122	257	29	29	**223**	277	501	263	**123**	183
18	246	**223**	263	**223**	140	140	245	276	90	501	**197**	**123**
19	507	189	160	189	**126**	**126**	248	354	471	471	361	361
20	**146**	241	257	241	474	474	276	245	296	500	39	39
21	529	122	241	122	177	177	309	380	323	282	203	203
22	537	263	298	160	263	263	287	**223**	353	296	442	442
23	368	99	168	263	257	257	329	309	418	323	298	298
24	34	80	170	99	183	183	243	329	500	86	369	369
25	9	177	140	80	19	19	335	248	376	376	**146**	**146**
26	241	9	125	177	170	170	354	335	86	34	173	173

27	263	168	215	9	442	442	52	287	34	535	76	351
28	95	298	173	168	298	298	334	474	56	241	357	76
29	318	170	99	298	99	99	500	500	241	418	343	357
30	27	173	189	145	122	122	471	52	535	56	351	343

Table S4. 2: Contextual information for some of the 30 receiving sites with the highest total inflow of plastic debris. Orange cells highlight variability in inflow (column Flows) from sources within the same estuary, dark blue cells highlight high social benefit from a smaller estuary, albeit stretched over a long area of coastline (coast) without any mapped reefs (reef), marine protected areas (mpa) or key biodiversity areas (kba). Abbreviated info on habitat values in second last column. For the full list of top 30 polluted sites see Table S5.1.

	Information on receiving site				**Information on main sources of pollution**				**Information on values**	
Rank Main source name	**Site ID**	**Site area [km²]**	**Pollution at site [t]**	**Count of polluting sources**	**Main three sources**	**Fractions [t]**	**River load [t]**	**Flows [t]**	**Mapped ecological value and area [km²]**	**People within 8 km vicinity**
1 Yangtze	675	6272	1041	101	196, 197, 195	0.36, 0.34, 0.24	82921, 82921, 82921	373, 355, 261	coast (6272 km²)	230.609
2 Yangtze	647	2688	1023	42	196, 197, 195	0.36, 0.36, 0.26	82921, 82921, 82921	376, 373, 271	coast (99 km²) mpa (67 km²) coast + mpa (65 km²) coast + bio (65 km²) mpa + bio (5 km²) coast + mpa + bio (91 km²)	13.077
3 Yangtze	662	256	945	46	195, 196, 197	0.39, 0.36, 0.23	82921, 82921, 82921	371, 348, 224	bio (149 km²)	8800
11 Modao-men Shidao	906	10.944	567	140	146, 149, 140	0.47, 0.17, 0.06	59003, 21698, 8440	268, 98, 38	coast (10.944 km²)	763.172
17 Ganges	591	2624	404	16	197, 196, 195	0.67, 0.28, 0.03	82921, 82921, 82921	271, 119, 13	mpa (1870 km²)	2575
19 Ganges	947	1792	325	27	15, 16, 13	0.49, 0.48, 0.01	35420, 35420 1915	160, 158, 4	coast (171 km²) coast + mpa (3 km²) coast + bio (274 km²) coast + mpa + bio (<1 km²)	25.794
20 Ganges	946	640	312	26	16, 15, 17	0.51, 0.47, 0.01	35420, 35420 35420	160, 147, 1	bio (442 km²)	25.897
25 Modao-men Shidao	146	64	254	78	146, 145, 162	0.99, 0.00, 0.00	59003, 2775, 7622	252, 1, 0.1	coast (64 km²)	1532
45 Bay of Manila	125 6	1600	159	47	255 257 256	0.73, 0.19, 0.04	25992, 7314, 1798	117, 31, 7	coast (317 km²) coast + reef (2 km²) coast + mpa (<1 km²) coast + bio (<1 km²) coast + mpa + bio (<1 km²)	28.715

Supplementary material S5.3: Metrics for highly polluted sites and their sources of pollution

Many of the most polluted sites receive inflow from multiple rivers but seem to have one or few dominant sources (Table S5.2, column count of polluting sources and flows). Only some of the most polluted sites have either larger areas of environmental value or high population density (Table S5.2).

Of the 542 potential sites within rivers available for site selection in our case study, only 32 contributed more than 100 tonnes to the accumulating plastic debris across all receiving sites. An inflow of debris was found for 4,008 receiving sites, and the volume of plastic debris arriving at each site varied substantially. 1,770 sites received less than 100 kg, and 2,925 sites received less than 1 tonne of plastic debris. Only 703 sites received between 1 to 10 tons of plastic debris, 380 sites between 10 and 100 tonnes of pollution, 77 sites received between 100 and 1000 tonnes of plastic debris, and two sites received more than 1,000 tonnes of plastic debris (Table S5.1, Table S5.2). Hundreds of sites received a large contribution of the incoming debris from one main source. Half of the 30 most polluted receiving sites did not contain any mapped areas of value, 14 of these located along the coastline, and one at the border of the modeled seascape. None of the 30 most polluted sites contained any reef, 13 contained key biodiversity areas, and 6 contained marine protected areas. The size of receiving sites in terms of the number of cells was not related to the volume of debris arriving, as a third of the 30 most polluted sites were single model cells. Sites with a high probability of receiving a large volume of debris were mostly sites in the direct vicinity of a source river. There was no correlation between the inflow of plastic debris to receiving sites and the coastal population density (Figure S4. 1).

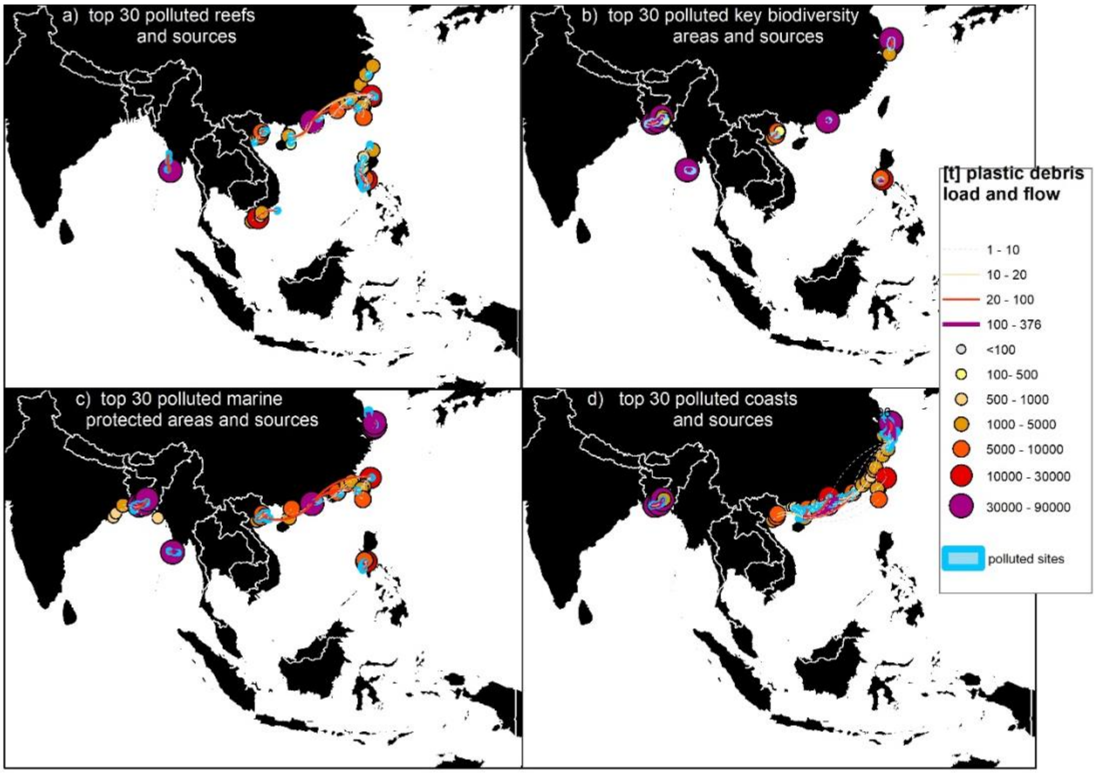

Figure S4. 3: The top 30 most polluted sites for each ecological value and general coastline, with the main sources of pollution.

Supplementary material S5.4: Sensitivity of metrics to different model scenario settings

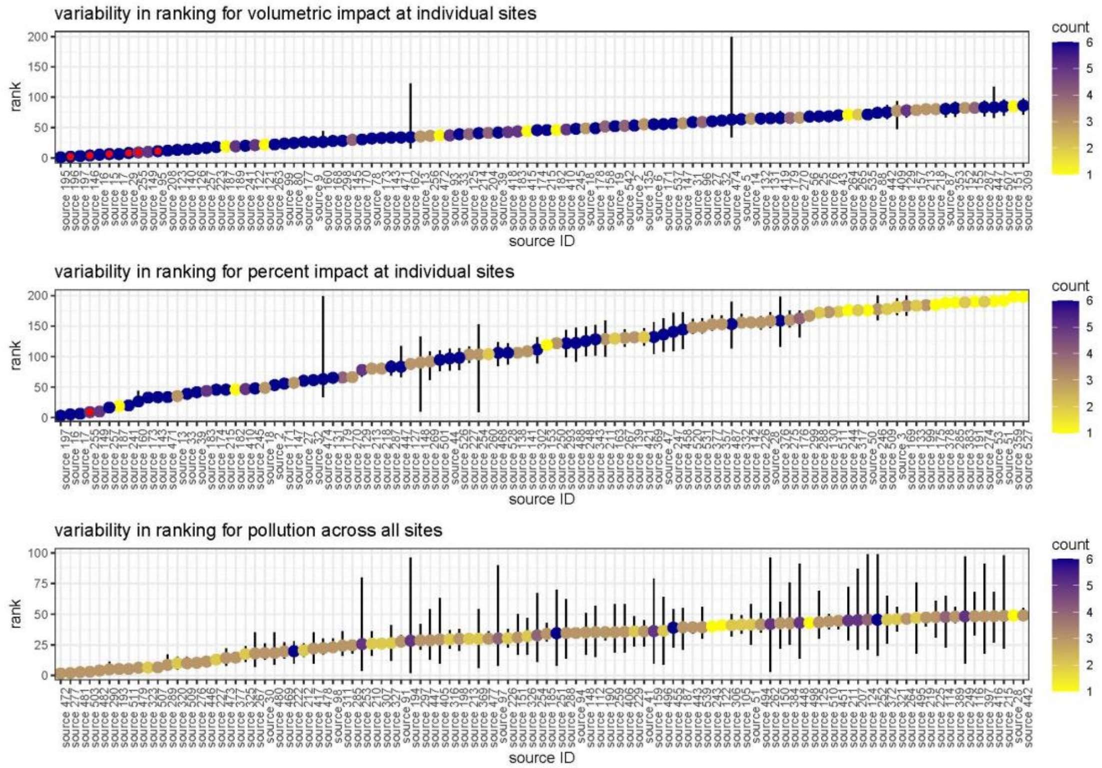

Figure S4. 4: Variability in ranking in the first 100 ranks based on variability in the reduction of variability in reduction in volume of inflow (Eq. 2, top panel, relative inflow (Equation 1, middle panel)) and variability in volume of debris in the source river (Eq. 3, bottom panel), across 6 different scenarios (shallow and deep currents, high and average load of plastic debris in rivers, high and low settlement rates). A count of 6 indicates that a high rank is robust under the full range of parameters across all scenarios, while a count of 1 indicates that a source is only ranking among the top 100 under a narrow range of conditions. Error bars indicate the magnitude of variability in ranks across all scenarios.

Appendix V: reviewer comments and responses for manuscript “10 years of decision-making for biodiversity conservation actions: A systematic literature review”

Letter of submission to Conservation Science and Practice

Dear Dr. Murcia,

I am pleased to submit the manuscript “10 years of decision-making for biodiversity conservation actions: A systematic literature review” and hope you are interested in publishing our work in Conservation Science and Practice.

Current attempts to halt and reverse the decline of biodiversity and ecosystem services seem to be failing on large scales. One of the potential reasons for this could be the decision processes themselves and the lack of uptake of key decision elements for reducing the risk of failure after implementation. Drawing on over 400 publications, we have quantified how often different decision support frameworks and tools include key decision elements, in particular, a quantitative objective, a clear theory of change, consideration of socio-economic constraints, sensitivity analysis and deliberation on trade-offs.

We have previously submitted this manuscript to Conservation Letters and Conservation Biology. In both instances, reviewers have provided helpful comments and suggested we resubmit to Conservation Science and Practice after we address existing reviewer concerns and suggestions.

A primary concern of reviewers was our framing of the study, the representativeness of our sample and the classification scheme we used to characterise how individual studies addressed key elements within decision support frameworks and tools.

Reviewers from Conservation Letters were mainly concerned about the initial framing. They had seen the label of "best practice" based on the use of all listed key elements as too judgmental and pointed out that quantitative evidence for the direct link between decision processes and quality of outcomes is limited. We agree that evidence about the link between decision support frameworks and the quality of decisions is limited. However, decision science is based on strong theoretical principles that have led to its adoption in a wide variety of settings including economics, health and defence (Wintle et al. 2011). We reframed our study by rewriting the introduction and discussion and dropping the label of "best practice", now focussing on our collected data that documents how often the use of key elements has been described in applications of different decision support tools and frameworks, and inferring what this may mean for conservation management.

We have also added examples of our classification approach to the main text and Supplementary Material to illustrate our classification rules and to avoid confusion among readers about their implementation.

Conservation Biology reviewers had a different set of concerns, possibly driven by an unfortunate lack of access to the Supplementary Material. Most details (and apparent omissions from the main text) that were criticized for being missing were available in the Supplementary Material. To reduce the length of the main text we placed methodological details that were not directly relevant to the results in the Supplementary Material. We still believe this to be justified but would, of course, be willing to bring specific information back into the main text if you think it is necessary and the word limit allows for it.

Reviewers had conflicting views about the representativeness of our literature sample. We argue that over 400 papers are a good sample. Although we can understand the concern that an analysis of grey literature might produce different results, we have addressed this in discussion. Based on our results, we do not see how a grey literature search would lead to fundamentally different outcomes and argue that the peer-reviewed literature remains a primary evidence base. In our study, we made a specific distinction between theoretical papers and evidently applied examples in our classification. About a third of our sample consisted, according to our classification criteria, of conservation practice examples. The use of key decision support elements was more strongly related to the use of specific frameworks than to the context of conservation practice vs academic examples. Hence, we believe concern about the representativeness of our sample to be unwarranted. We have added this line of reasoning to our discussion.

Finally, we addressed a reviewer's concern that our search terms excluded some important decision-aiding frameworks by checking WoS for terms they recommended but did not find any new descriptions of conservation decisions. We reflect that we have a (good) sample of the conservation science literature that covers the uses of primary frameworks and tools described in Schwartz et al. 2018 and Bower et al. 2018.

In addition to addressing reviewer comments, we made minor changes throughout the text for clarity and flow, and added some additional references, all in tracked changes or marked up with a comment.

This submitted work has not been published and is not under consideration for publication elsewhere, all authors have approved this submission, and all persons entitled to authorship have been named. All data and code are made available on figshare (https://doi.org/10.6084/m9.figshare.17205713.v1).

Please find below a detailed response to all reviewer comments we received through our submissions to Conservation Letter and Conservation Biology. We hope to demonstrate that we dealt with all concerns and hope for a publication with Conservation Science and Practice.

With best regards,

Jutta Beher

Conservation Biology: Response of editor and comments of reviewers

Authors responses to editor and reviewers' comments in blue

Editor's comments

27-Jan-2022

Dear Ms. Beher,

Thank you for submitting your manuscript "10 years of decision-making for biodiversity conservation actions: A quantitative literature review" (21-774) to Conservation Biology. I have received three thorough, constructive reviews and the comments and recommendation of the North American Regional Editor, Professor Resit Akçakaya. The full set of comments is pasted below.

All three reviewers appreciated the focus and motivation for this submission. Unfortunately, all three also noted significant concerns regarding the framing of the study and the assumptions underlying the analyses and recommended major revision or rejection. On the basis of the reviews and recommendations, I must decline the manuscript.

However, the study is well motivated and if you can provide evidence that the sample is representative of the true population of conservation decision making, or if you can define better the relevance of the sample, I encourage you to submit a revised manuscript that includes appropriate caveats, perhaps to our companion journal, Conservation Science and Practice. Thanks again. Best of luck in publishing your work and in applying your insights to inform the practice of conservation.

Sincerely,

Mark Burgman

Editor in Chief, Conservation Biology

Regarding the highlighted requests from Mark Burgman above (in yellow), please see paragraphs starting at line 48, 149, 206, 223, 352, 384, 433, 458, 497, 519, 533, regarding evidence of the representativeness of our sample in this letter, and line 521 in the manuscript, where we expanded our discussion to cover caveats of the study, including the question of representativeness.

All changes in the manuscript are tracked in mark up.

Regional editor's comments

Comments to the Author:

This study presents a major review of literature on conservation decisions. Although the reviewers recognize the importance of the topic, and appreciate the effort that has gone into this analysis, they have also identified fundamental shortcomings, and expressed serious concerns.

One main issue is that, as partially acknowledged by the authors, academic publications on conservation decisions are not necessarily representative of the decisions made in conservation.

We fully agree that peer reviewed publications on conservation decisions are not necessarily representative of decisions made in conservation. However, peer reviewed publications are an important lens to use when investigating questions of decision quality, as this pool of examples is the most accessible set of examples to scientific scholars. Publications and references to publications are the building blocks of knowledge, and what scientists publish and cite informs not only the academic debate but is also used among politicians and managers to argue for (or against) applications in the real world.

We also would like to point out that we have tried to address the concerns about representativeness already by categorising publications into groups depending on the explicit mentioning of any implementation or collaboration with decision-makers who are eager to use the work. We found that a third of the sample contained a statement that the study resulted either in implementation or was a collaboration with decision-making authorities. We therefore believe that the database we have built provides an important insight into the type of decision problems conservation scientists work on, as well as the decision-elements that they include or not include.

Another major issue is the assumption that all decisions in conservation require the same set of key elements. In addition, reviewers also questioned the specific framework and key elements that this study has focused on, and other aspects of the methods.

We would like to question the criticism to apply insights from decision science to conservation decisions. See also comment and response in line 107ff. Even though there will always be arguments for or against the use of specific elements during a decision process, it is important to acknowledge that no element should be omitted without a good reason. We have framed our study not around the argument that all elements have to be at all times included, but to be aware that some frameworks seem to be more effective than others to push users to consider them. This insight alone can have important implications, especially when people who use these frameworks do not have themselves deeper knowledge about decision-science. The decision to include or not include a specific element that had been highlighted in decision science as important should be a conscious decision and not the consequence of being unaware. We address comments regarding these topics in lines 107, 149, 223, 362, 433, 458, 497, 519 and 533 .

Reviewer 1

Comments to the Author

The abstract should include the time period of the literature review, making it relevant to the manuscript title.

We have included the time period in to the abstract (line 24), we agree that this improves effective screening.

Line 48-51. This reviewer thinks that the authors should provide a brief exposition on this in the manuscript. The Abstract says “it has been demonstrated that decision-makers can increase the chances of achieving conservation aims” but there is no discussion of this in the manuscript (with citations to empirical research). Readers will be interested in how the existence of sound decision-making elements improve outcomes?

We have provided this information in the Supplementary Material, in particular, the importance of each element, including several references, and hope that it will be available for reviewers in case another round of review is necessary. In addition, we have slightly reworded the sentence and provided more information with references in the introduction in line 61ff.

Line 48 and Lines 96-101. What is the intent of ensuring that all key elements are "utilized" in decision-making? We must not assume that every decision requires each key element to achieve desired outcomes (see Figure 1 in Keeney 2004, DOI: 10.1287/deca.1040.0009). A quality decision can be reached by only considering a sub-set of necessary elements, as needed. It should be clear that failure to explain some elements in a research study does not limit the study's credibility in any way unless there is more information to make that determination, such as postmortem revelations like hidden objectives or irrational thinking. The authors could be biasing the analysis if they assume that research studies without all elements is faulty or of lower quality in any way. This is where examples would be very useful to accompany related discussion points in the Discussion section. Recognizing that publications frequently omit key decision elements doesn't necessarily infer poor quality decisions. The examples in the submitted manuscript are shallow and cursory.

As per previous comment, we assume this comment stems from the unfortunate situation that reviewers did not have access to the Supplementary Material. We have outlined there in detail why each element is important and needs to be considered. We agree that there might be examples that do not require each element for specific reasons, but we believe firmly that these are exceptions and authors should highlight the circumstances that make the specific element obsolete.

While we agree that more specific examples could help readers understand the choice of elements better, we need to still be concise in our manuscript and are bound by a word limit. Our paper is not a review on decision theory but draws upon well-established principles. We have included multiple references for the evidence base of decision science in general (for example, line 61 ff), as well as documentation of the consequences of neglecting each of these elements in conservation decision-making (line 118 ff). While we agree that the figure in Keeney 2004 states that not all elements turn out to play an important role to resolve a decision, it does not state at all that these elements should not be thought about during the decision-making process. Decision science advises to think about these elements to assess their importance, and to avoid regretting in hindsight to not have thought about them during the planning. A well-documented decision process should be transparent about the details that were deemed relevant for each element in the decision, so that other people can understand the decision. If the rationale for a decision can't be understood, the value of the description of the process is reduced. Our review aims to provide an overview on how well the different frameworks lead to transparent and complete descriptions of decisions, that can be useful for others to learn from. We have also added references that support the line of evidence that attention to process and key elements will likely improve outcomes for conservation, including Kellon et al. 2011 (line 73), Rose et al. 2019 (line 74), Watermayer et al. (line 70),

Lines 56-57. The following passage (Lines 57-66) does not affirm this statement. For example, it should be clear how SDM utilizes a distinct step in decision-making because this reviewer cannot affirm this line of thinking.

I apologise, but I am not sure I understand the comment.

Lines 51-66 & Table 1. This reviewer wants to know why the authors chose the frameworks to review. They do not clarify why the frameworks were chosen other than to suggest that they are common. Stating that they are "frequently used" or "common" is insufficient and can severely limit the discussion points (see below example of the narrow view of SDM worldwide). Systematic Conservation Planning or SCP addresses only one type of decision problem, namely the reserve design problem. This has been foundational to mathematical programming studies in Australia. Adaptive Management is an extension of decision making, meaning that it can be applied after (or in some cases as part of) SCP, SDM, MCDA, or CEA, meaning that it is not explicitly comparable to the others. SDM is largely a North American concept and is intentionally flexible to include SCP problems and MCDA & CEA analyses. Likewise, MCDA & CEA are strictly analytical approaches to evaluate trade-offs, which is only one key element of a decision process. The Schwartz paper missed the mark on these distinctions and why they are not really comparable. This reviewer wonders why these frameworks were chosen and, hence, why other frameworks that explicitly address other types of decision problems or other elements were eliminated from consideration? Explicitly stating the assumptions up-front and their limitations in Discussion is warranted

We acknowledge that there are many other ways of making decisions, which are possibly also relevant to conservation decisions. The frameworks we included have been referenced as common tools to aid decisions in conservation in other publications, and we believe our large sample size confirms that these tools are indeed used to aid decision making in conservation. A review on the details of the decision process across these tools is in our view a timely and useful investigation, as it has not been done, and could have important implications on conservation planning. Search for other frameworks in our initial search as well as in additional searches based on the few suggestions from reviewers did not find additional studies that describe a decision process in conservation. We describe in detail that the included frameworks and tools have been developed for specific purposes in mind (see Table 1 in the manuscript). A certain degree of overlap is to be expected, as all intend to help people make decisions about conservation problems. We have allowed for multiple entries during the coding to reflect if several frameworks or tools have been combined. We disagree with the statement that these frameworks and tools are not comparable. Our evidence base shows clearly that all of them are used as stand-alone decision aid to make a decision in the context of a complex conservation problem. Our figure 3 shows clearly that all frameworks and tools get applied to some extent to the different types of conservation problems. Our clear findings and the large sample size confirm in our view that the evaluation through the lens of decision science is justified, because the lack of rigour in decisions has been discussed in many publications, for example, see Game et al 2013 (and line 129 ff in the manuscript). The amount of work to review and classify over 400 publications was considerable, and we believe we have covered a lot of ground, with sighting over 1200 publications in detail. We have coded all examples with classifications that apply to multiple frameworks and tools. We regret that the reviewer has not given more detail on the specific names of the frameworks that he believes were missing.

Table 1. What is meant by "without compromising objectives" under CEA? It is this reviewer's understanding that all objectives, including but not limited to costs, can be considered in a CEA.

We mean by this sentence that objectives other than cost exist, and are not compromised, as CEA is aiming to find the most cost-effective way to meet the objective. We have added "other than cost" to avoid confusion.

Line 50. Robin Gregory is the first of many authors of the SDM book. Please revise this and all remaining citations and the reference.

We apologise for this and have updated the entry in our reference software and in all references throughout the manuscript.

Line 61-63. Include citation for this statement.

We are unsure why such a general statement would need an own reference after we summarized decision science, frameworks, tools and key elements in the previous paragraphs. The sentence "This recognizes that each decision context may require a suite of different detail in each broad phase. While vagueness within decision support options provides flexibility to account for context, it can lead to unintended neglect of the fundamental needs of each key decision element" is somewhat also covering the differences between the tools which the reviewer stated in his previous comment.

Lines 67-73 and Table 2. Gregory's SDM book is not a fundamental decision theory text. If the authors wish to keep this citation, suggest eliminating the word "fundamental." In addition to clarifying why the frameworks were chosen (see above), the authors should be clear about their assumptions on choosing the five crucial elements of a decision process. I don't have access to the Supplemental material, but there should be some discussion about their assumptions in the main text. For example, this reviewer does not affirm that documenting constraints is a crucial element for all decisions. The authors suggested some examples of constraints are costs or feasibility (Line 93), which is inconsistent with how they are used in the Gregory book and other foundational decision theory texts as objectives. Table 2 uses the phrase "socio-economic considerations" instead of constraints, which is inconsistent. Foundational decision theory texts use the term "objectives" to call out all dimensions of a decision process, whether they are financial, social, ecological, etc. The authors are potentially creating a distinction that doesn't existing in the foundational decision literature, which can lead to confusion. Further, dealing with constraints is only a sub-heading of Gregory's book (Section 7.3.4), which is principally focused on whether there are targets or limitations for any objectives that require careful consideration. .

We thank the reviewer for alerting us to the lack of nuance in the text. We have added "in the context of conservation" to the reference to make a distinction to the more classical fundamental decision theory texts (line 103). We believe access to the Supplementary Material provides ample explanation of why the elements we included in our review are important. We acknowledge that without having had the opportunity to look at these sections, questions about our motivation can arise. Regarding the language around objectives, constraints and considerations, we believe there is a linguistic hierarchy here, that we did not spell out. To become an objective during decision-making, there needs to be consideration, and the specific way an objective is addressed depends on the objective function used, which can be defined as a constraint, or a target or other quantifiable expression (see Nicholson 2006 about Objectives for multiple-species conservation planning which we cite in the section of objectives).

Additionally, Gregory's book is organized around the Problem-Objectives-Alternatives-Consequences-Tradeoffs or PrOACT framework (Hammond et al. 1999, Smart Choices). In addition to PrOACT, there are other frameworks that provide other crucial elements, such as the "logically correct reasoning" or "commitment to action" elements of decision quality (see Matheson & Matheson 1998, The Smart Organization; or any decision quality papers by Carl Spetzler, or Spetzler's book Decision Quality: https://sdg.com/decision-quality-book/). Were they considered ?

We appreciate the suggestion of additional decision science frameworks, however, we chose frameworks that were to our knowledge commonly used in the conservation sciences. We could not find any entries in the WoS core catalogue that would fit our objective to find examples of biodiversity conservation decisions with the suggested key words "PrOACT", "logically correct reasoning" or "commitment to action".

We acknowledge that Robin Gregory did not invent the wheel, but rather introduced an important framework into the context of biodiversity conservation. We have made this clearer by adding "in the context of conservation" in line 103.

We would also like to point out that the key elements we use in our assessment align well with the decision quality indicators on the suggested website. The decision framing is reflected by our quantitative objectives as well as socio-economic considerations, the alternatives are an inherit part of the selected studies (decisions for alternative management actions), relevant and reliable information is captured by the sensitivity and scenario analyses, sound reasoning is captured by the clear theory of change, and understanding potential outcomes is reflected in the trade-off analysis (see https://sdg.com/wp-content/uploads/2016/01/Decision-Makers-Rights.pdf). Commitment to action is in our case not relevant, as we focused on the decision process. To a certain extent, commitment to action is captured in our classification of level of implementation.

Line 68 "against which to evaluate conservation publications." The reader has not been introduced to the frame of this paper yet. Suggest creating a new paragraph to set up the present literature review study, taking into consideration the above comments.

While an alternative structure could surely also work, we would prefer to keep the details of the literature review in the methods section.

Line 118. What does “adequate detail” mean here? Can the authors provide an example of a publication that was eliminated based on insufficient detail?

Adequate detail means that the paper gave enough detail to understand what the decision was about, and what information was taken into consideration during the decision process. Finding an example would be possible but would require sighting the >600 papers again that were sorted out during screening, and the gained benefit for clarity in the text likely does not justify the workload of doing that. We have added “to understand the decision process” (now line 159) to the sentence and hope that this help to understand the sentence. If this suggestion is seen as crucial I can invest the time.

Line 119-121. Again, an example of a publication that described multiple decisions would bring clarity to the review.

We are happy to give Canessa et al. 2016 as an example in the text in line 163.

Lines 147-149. This reviewer does not understand the distinctions that are being made between real-world and academic. A structured decision process is intended to provide useful insights into a decision, not necessarily to take action or implementation. There is a distinction missing here and likely relates back to why Adaptive Management is dissimilar from the other frameworks presented. This reviewer and many others have published studies on how a structured decision process clarified decision insights in real-world contexts. Although these decision insights have led to real decisions, the publications largely exist clarify the assumptions and modeling included in the process leading up to a decision. It appears that these would be labeled “academic,” which doesn’t make a lot of sense. Please clarify.

We are sorry that the reviewer did not understand our distinction between "academic" and "conservation practice" (previously named "real world") examples. We described in Table 2 that "conservation practice" examples included a statement in the text that the decision described had either already led to implementation or had been conducted in collaboration with management authorities. A statement about the level of implementation or collaboration with decision makers in a publication is the only way readers (and authors of literature reviews) can interpret the context of a case study regarding likely impact on real world decisions. We acknowledge that this method has shortcomings, which we also already address in the discussion in our section on limitations. We are not sure how to improve what we have written and done but are of course open to more specific suggestions.

Lines 119-121 and Figure 2a. If a publication described two different frameworks, such as SCP and CEA, how were they evaluated? Many publications using the SDM framework have included MCDA and CEA analyses, which is why the choice of frameworks in this study is confusing.

We have the category "mixed" which indicates that a mix of frameworks were used. We thought this was self-explanatory, but have now added ", or "mixed" if more than one was used" in Table 2.

Lines 176-177. How can a publication discuss a decision process without acknowledging the objectives for that decision? In the other half of examples, or examples where objectives were not described, what was evaluated? What were the actions trying to achieve (without stating objectives)? How was performance evaluated under different sensitivity scenarios (without stating objectives)? How were tradeoffs between decision options evaluated (without stating objectives)? Examples of this result would be good to include.

We explain in more detail what type of objectives were considered as “clear” in the Supplementary Material S1. The examples that were classified for missing a clear objective did either not describe what they wanted to achieve in detail or were limited to target specific threats without having a clear aim what the objective for the biodiversity of value (such as species or habitat) would or should be. We understand that an example could be helpful. We have added Briceno et al in line 426 in the discussion part of the manuscript.

Examples for missing quantitative objective:

1) Choulak et al. prioritise wetlands for prioritisation, without any information on how much wetlands needs to be protected.

2) Briceno et al. compare interventions against poaching for yellow shouldered parrots, but do not provide any objective of to what level of poaching need to be reduced to keep the population at viable levels.

3) Koehn et al. provide information on how to make trade-offs between conservation and use of a threatened fish species, but do not set any quantitative objective for the conservation objective, which is in line with the lack of final trade-off, leaving these details to decision-makers that might want to use their method.

Lines 195-197. Again, how can a CEA study not include quantitative objectives? What would represent the “effectiveness” part of the CEA in these ‘conservation’ studies? Without examples, this paper can be very confusing to readers.

Thank you for bringing to our attention that the wording could be confusing. As our review is about conservation decisions, we were looking for quantitative objectives that were related to conservation outcomes, based on a clearly articulated theory of change. We have edited the sentence in line 252 of the manuscript to “quantitative objectives for the biodiversity value that was supposed to benefit from the management” to be clearer. We agree that an example is helpful to understand, and have added examples in addition in line 425 ff in the discussion. To further illustrate here some more details:

1) Martin Otega present a waterquality study that is supposed to benefit waterfowl, but does not set any quantitative objective regarding waterfowl, only for pollution reduction without any clear description on how changes in pollution reduction impact the species.

2) Bouma present a sediment runoff study that is supposed to benefit the GBR, but do not refer to any specific species or ecological target, only present runoff abatement costs. They acknowledge explicitly the uncertainty around the reduction of TSS pollution and GBR health and stay very vague about the actual ecological benefits that would be expected.

3) Johnson et al describe the control of invasive lizards, without a quantitative objective for the biodiversity that should benefit from this control.

Line 218 and Figure 3. What is meant by “mixed” on the x-axis? According to the text, it appears that mixed means management strategy (e.g. spatial prioritization, restoration, etc.), but why is it compared to the five frameworks in Figure 3a.

See our response in line 281 in this document. We have edited Table 2 to make it clearer that “mixed” refers to the use of multiple frameworks.

Lines 269-270. As stated earlier, this paper does not evaluate all key elements of decision science. Suggest clarifying assumptions in the methods and replacing “that did not apply key elements of decision science” to “did not apply the elements evaluated in this study.”

We have edited the sentence In line 339 in the manuscript to: But the bulk of academic and applied studies that we evaluated in this study that document decisions do not apply all of the key elements […]

Lines 277-279. This reviewer is confused with this statement. SDM is a framework that applies decision analysis, a well-established process that is over 70 years old, to environmental management decisions. Environmental applications of decision analysis existed for decades prior to naming them “SDM.” Likewise, MCDA and CEA are both based on decision science and over 70 years old as well. Classical Adaptive Management (based on Carl Walters’ foundational text) is also based on decision science concepts developed in the 1950s. As you can see, some readers might be confused by this statement.

We can see how our wording can lead to confusion. We have edited the sentence in line 355 to

Of the decision support frameworks we considered, structured decision making is the most recently developed framework, and therefore draws on the most complete suite of insights from decision science.

Lines 281-284. What are the potential shortcomings affecting decision-making and how did this literature review provide insights? If the authors are referring to the very short list on Lines 91-95, this reviewer doesn’t see the connection between these challenges and the literature review results.

We have given more detail on the consequences of not using these particular elements in the Supplementary Materials. Not having had access to this information was likely the cause of this comment. We could add some detail back into the discussion to make the link clearer. At the moment we refer to the Supplementary Material and address shortcomings linked to the key elements in the process of decision making in line 129 ff in the main text, as well as several new marked up examples in the discussion, mentioned in previous comments in this document.

Lines 286-288. Does this statement infer that a lack of key elements in a published study represents a shortcoming in decision making? This reviewer cannot affirm this based on this study without examples from the reviewed set of studies. The inferences made on Lines 308-311 and 388-391 relate to this and a related comment above.

We had tried our best to remove any judgmental language from the manuscript, and do not intend this sentence to be a judgment, we mean it as we wrote it: we discuss the potential reasons to use or not use these elements, and what this might have for negative consequences. We believe that is a valuable exercise, and this was the core motivation to do this study. We personally believe the use of elements is likely linked to the quality of decision processes but had strongly opposing views in past reviews. We had reworked the framing of the study to take judgmental wording out and instead just describe the findings and discuss potential consequences, without a binary judgment of good vs. bad. Of course, we cannot prevent readers to interpret the discussion of possible consequences as a general judgment, but again, this is not our intention. We have added several examples in results and discussion to illustrate the type of problem when key elements have not been included transparently in the studies.

Line 421 (and Lines 109-112). This study also contrasts with the trends found in Huang et al. 2011 (DOI: 10.1016/j.scitotenv.2011.06.022), which begs the question of how an “environmental problem” or “conservation-related decision-context” was defined in the Web of Science search. If “biodiversity conservation” was a significant determinant to excluding publications (Line 424), then it should be stated in the methods section. Other significant determinants might be the potentially limited search for the five frameworks, which are not all globally accepted. For example, it makes sense that studies from North America largely implemented SDM because SDM (as a phrase used to describe a framework) was developed by scientists from British Columbia and the United States. Other publications of the exact same framework (PrOACT), yet under the heading of “decision analysis,” may be present in much higher numbers everywhere else in the world, including Europe. This is a limitation of both the methods applied and inferences the authors can make.

We believe this comment stems as well from the apparent unfortunate situation that the Supplementary Material was not made available to the reviewers. We have provided the full search terms that state that we used key words to filter for biodiversity and conservation related context. We also like to disagree with the conclusion of the reviewer that “North America largely implemented SDM”. Although SDM studies were mainly from the US and Canada, other frameworks were much more frequently used in these countries, and SDM was also used in Australia. As mentioned in an earlier reply in line 223 ff, our subsequent check in WoS for ProACT did not return any conservation related publications.

Lines 437-440. If the Koehn & Todd 2012 paper mentioned tradeoffs but did not evaluate tradeoffs, how was it included in the list?

We included the example of Koehn et al to show how difficult a judgment on classification could be, and how important clear rules during the classification task are. The paper describes a decision process with a focus on nature conservation. They describe how to make a trade-off, but do not give a final recommendation of a best management option. We assessed all elements for their inclusion based on decision rules in our classification scheme, which we have described as transparent as possible, and this study was an example on the situation that an element can be mentioned in a study but gets classified as not being included. Any classification scheme will have such challenges, and we document one of these here in a very transparent way. We are not sure what the reviewer does not understand, or which list they refer to.

Lines 458-461. Agreed and would suggest also that, in addition to inspiration, that scientific literature is a good place to understand how fundamental guidance is used in different decision contexts.

We are glad the reviewer agrees that our study makes sense and will contribute to the understanding how fundamental guidance on decision making is used in different decision contexts.

Reviewer 2

Comments to the Author

GENERAL COMMENTS

This paper describes a review of conservation decision making approaches from a sample of the published literature. I think in general, this is a VERY important topic that needs to be carefully studied. But this paper seems to have some fatal flaws that would make it at best not helpful and at worst fundamentally misleading to publish.

I have major concerns about the basic premise of looking in the academic literature to develop a sample of conservation project decisions. In my experience, the vast majority of conservation decisions are made by practitioners who work for protected areas, conservation NGOs, or community groups and would never think to publish their work in a scientific journal. So it seems to me that at best, this is a highly biased sample of conservation decisions that (for better or worse) skews towards academically-minded implementors. And I wrote the above BEFORE I even got to the section in which the authors state that 2/3 of their sample cases are "academic" as opposed to "real-world." Can the authors provide evidence that their sample actually represents the population of conservation practice beyond the unsatisfactory arguments in the "Representativeness of Results" section? Because if not, then I don't think it's appropriate to draw conclusions about this wider practice.

We would like to note that this is in direct contrast to the opinion of reviewer 1, who states that "that scientific literature is a good place to understand how fundamental guidance is used in different decision contexts".

We acknowledge that using white literature as a sample to discuss decision-making for conservation in general can be viewed as contentious. However, the conservation scientific community depends on these publications to discuss and broaden the knowledge of how decision about conservation projects can and should be made. A similarly large sample of grey literature that covers that many countries and types of conservation problems would have been an enormous task. We also would like to repeat that we addressed these limitations by specifically coding for indication that any publication was linked to a conservation practice project. Our comparison between the differences of implementation context and frameworks shows that the frameworks have a larger impact on the use of key decision elements than the explicit statements that a project was implemented or done in collaboration with a management authority. This should give confidence that the differences we found are linked to the instructions of the particular frameworks, and that these results are of interest to the users of these frameworks, both academics as well as all the other more applied groups that work outside of academia.

We also are not sure in which way the reviewer questions that our sample of over 100 examples of "real world" (now "conservation practice") decisions is not representative. For example, do they mean in terms of frameworks used? Or do they believe there will be differences in the type of conservation problem and the strategies to approach them in examples from the grey literature? It would have been interesting to learn what other frameworks were believed to be more dominant outside of academia to enable an additional WoS search, as we did for the suggestion of "ProACt".

My second set of concerns has to do with the authors' definition of good decision making. The "five crucial elements of a robust decision process" seem to be somewhat haphazardly pulled from Gregory et al; I personally could think of several equally important elements. And even if we accept these elements, the authors seem to make a potentially tautological argument being made by using this Structured Decision Making text to define the elements of good decision making and then concluding that the Structured Decision Making examples in their study best fulfil these elements.

We have dedicated an extensive section in the Supplementary Materials that gives evidence and reference to the many studies that have focused on these elements in conservation decisions, and the consequences when they are omitted. We therefore disagree that our selection is "somewhat haphazardly pulled" from Gregory et al. and believe this is another unfortunate consequence of not having had access to the Supplementary Material. As we have acknowledged in the discussion, Gregory et al. have contributed the most recent framework of the collection of decision support that are used in conservation, and has leaned strongly on decision-scientific texts, which makes it likely that people that use this particular framework follow more likely guidance from decision science than when other frameworks are used.

DETAILED COMMENTS

Line 2: I assume the authors mean to write “A quantitative literature REVIEW”? I personally think that given the biased nature of the sample (see below), it is misleading to say that this is a “quantitative” review.

We apologise that this important word has been lost during the upload and have added it to the title again. We are also happy to change the title to “a systematic literature review”. However, we are not aware of any review that gives an overview of more than 466 examples in this detail and think quantitative would be a correct description of our work.

Line 37: The authors state “It is not possible to determine whether the strategies developed to stem biodiversity decline are flawed or sound but implemented at too small a scale with inadequate resources.” While this statement may be true if we want to precisely quantify the relative proportion, I think it’s pretty obvious that the truth is some combination of the two. I would find some way to reword this sentence to be less declarative.

We agree that the truth likely lies in between, it was not our intention to create the impression it is either one or the other. We have changed the sentence in line 55 in the manuscript to “It is not possible to determine to which extent the strategies…”

Line 42: This “call for greater attention” has been going on for decades now.

Indeed, and unfortunately it has not been answered yet, what has sparked our motivation to do our review.

Lines 67-74: How were these five elements identified compared to others? Off the top of my head, I can think of other seemingly equally important elements such as “understand the situation,” “assess available evidence for different options” and “monitor, evaluate, and adapt” among others.... The authors cite Gregory (2012) but that book lists 7 key questions that need to be addressed, which include some of the missing elements that I identified above and then 6 steps in a structured decision making process.

As stated in the response to several other comments (see, for example, line 91ff, 107ff, 206ff, 352ff, 384ff, 458ff), we believe access to the Supplementary Material section on the importance of these elements could have prevented this comment. We also would argue that “understanding the situation” is more or less equivalent to having a clear concept of cause and effect (which is our threat category), “assess available evidence for different options” is the same or at least very similar to conducting a scenario or sensitivity analysis around different options, and “monitor evaluate and adapt” comes AFTER a first decision has been made. The insights from monitoring can then be used again as input into a consecutive decision and can inform either the quantitative objective (insight that for example a larger threshold is needed), or another factor has been overlooked (which links into the assumption of cause and effect), or other issues like cost or feasibility were detected as problems.

Line 67 and Line 548: Gregory should be Gregory et al. – there are 6 co-authors.

We apologise for this truncated literature reference and have edited our database and updated the references in the manuscript accordingly.

Line 69: Should "publications" be "decisions" or some other word? Seems nonsensical here.

We refer to the database of publications that we have evaluated. We have updated the wording to "published descriptions of conservation focused decision processes" to be clearer (line 105), thank you for alerting us that clarity could be improved here.

Line 128: Per my general comment above, it's a bit of false precision to document accuracy in classifying the sample when the underlying sample is likely incredibly highly biased.

We are not sure if the reviewer is of the opinion that peer reviewed publications should not be used for conservation related reviews because they are primarily written by academics? We are very transparent about the limitations and have provided the category of implementation context to account for potential large difference between more academic and more applied work. As stated above, the differences we found between frameworks were more obvious than between the implementation categories. We therefore believe that our study still provides very relevant information for anyone who works in conservation science and deals with different decision-aiding tools. We agree that the number of examples of different frameworks and decision contexts are not evenly distributed, but we do not agree that this makes the data irrelevant, the differences in the sample size is part of the results that we discuss.

Line 146: The fact that 2/3 (!!) of the sample examples are "academic" and not "real-world" even more reinforces my point about the biased nature of this sample. Why would you include these "academic" examples in the sample?

We are not sure why the reviewer believes that academic examples of conservation decisions are not relevant. Many of these studies are done out of the motivation to provide guidance and inspiration for practitioners on how they can make better decisions.

We also believe that not every uneven distribution is necessarily a bias that makes the whole dataset unusable. On the contrary, we were positively surprised that almost a third of the studies in the academic literature stems actually from applied contexts.

One objective was to find out if the context drives differences in how often elements get explicitly addressed, or if these differences are rather linked to the different decision-aiding tools that are used. As our study clearly shows, the second is the case. We believe this is an important insight.

Line 227: Isn't systematic conservation planning basically just a method for doing spatial prioritization??

All decision-supporting tools help to make prioritisations. SCP has a focus on spatial decisions. We are not sure what the question is, or why this is a problem. We have included several common frameworks to cover different aspects of conservation problems, and decisions about the placement of conservation areas is one important decision context.

Line 277: The statement that since SDM is the only recently developed framework, it is therefore the only one fully based on insights from decision science is a bit misleading. The other frameworks that I am familiar with have gone through multiple iterations and have incorporated key elements from decision science. Furthermore, there is an inherently tautological argument here in that the authors define their key elements for good decision making based on a seminal SDM text (Gregory et al.) and then 'surprise' find that SDM fulfils the most of these elements. If they had defined their elements based on some other approach, it seems likely those other approaches would have scored higher….

We disagree with the interpretation that we have taken our elements from SDM. As outlined above, these elements are part of decision-science, and have been evaluated in many studies (as explained in the section on the Supplementary Material), often dated before SDM entered the stage. We believe the reviewer misinterpreted the overlap between elements in SDM with key element from decision science as evidence that we took the set of elements from Gregory et al.

Line 281: Given the biased sample and the tautological arguments, not sure the authors really can claim "We believe our results provide great insights into the potential shortcomings affecting decision-making, and highlight opportunities for more transparent reporting of important decision elements in publications."

We hope we have provided enough arguments in responses in lines 48, 107, 149, 206, 223, 352, 362, 384, 433, 458, 497, 519, 533, 716, and 739, to make the case that our results are relevant, and our sample is representative.

Line 338: It seems a bit weak to say there are few examples of Adaptive Management success stories and then only cite references from 2006 and 2012 – and those from Gregory who works on SDM. There has been a huge explosion of adaptive management work in the past decade. Likewise, the "recent" review was published in 2013?!

We are not the first authors to point out that Adaptive Management is unfortunately not often used to its full potential. We merely point out that it can done well, and Gregory is one of the authors who has demonstrated this. We have checked for each framework if the use of elements changes over time and did not find any clear effect. We admit that we did not engage in a full extensive statistical analysis to test for a change over time for the use of AM. Unfortunately, the “most recent review” was the most recent review that we found. If the reviewer is aware of a more recent one, it would have been helpful to reference it, so we could have included a more recent publication.

Line 411: I appreciate that the authors try to look at the representativeness of their results which is my main critique of this work. But I’m not convinced by the arguments here. At best, they argue that 1/3 of their papers are “real-world” and that their observed frequency of publications that use Multi-Criteria-Decision-Analysis is similar to another academic review. But how does their sample compare the actual population of conservation actions, projects, or programs??

This is a great question, but without a review on grey literature, which has been to our knowledge not done yet, we are not sure how to answer it. This is one of the reasons why we have started with the peer reviewed literature, as it is available, searchable, and in the English language. Other published reviews of the white literature on similar topics have made implications on conservation outcomes and have been published in prestigious journals. We therefore disagree that only grey literature can be used to provide useful information about conservation science and practice.

Table 1. As the authors point out in the text, Multi-Criteria-Decision-Analysis and Cost-Effectiveness Analysis are just methods that can be incorporated in the other

approaches. It’s not clear to me that it is really appropriate to rate/study them in the same way as the others.

As there are many examples that use these decision-aiding tools as stand-alone decision help to inform the choice of conservation management actions, we were of the opinion that this justifies their inclusion. In contrast to the many examples we found for Cost-effectiveness and Multi Criteria Decision analysis, Horizon Scanning and Strategic Foresight, which have been described as highly relevant by Schwartz et al,, did not return any examples in our search. We therefore believe our review is, in addition to the insights into the use of decision-theoretical elements, also a reality check of what type of examples of decision processes can be found within a systematic literature search.

Table 2. I think “actions and threats” should actually be characterized as “appropriate situation analysis” or something like that.

We have explained in our infamous Supplementary Material why we use the description of explicit threats as a shortcut to classify for an understanding of cause and effect/ the problem context. This comment is also in direct contrast to a previous comment of this reviewer when he suggest that “understanding the context” would be missing from our list of elements (we have pointed out in our reply that we believe this is captured in our threat category).

Reviewer 3

Comments to the Author

General comments

This is an interesting manuscript, which reviews relevant information for conservation decision making based on data extraction from a large sample of publications and therefore of broad interest. The text is concise, perhaps too concise in many places. The results are unsurprising but present interest.

I have concerns on the repeatability of the process and the lack of incorporation of systematic review reporting standards such as PRISMA or ROSES. In addition, while I recognise that non-English and grey literature are comparatively difficult to include, the authors don't even mention these additional sources of information until late in the discussion.

We have provided a full description of our search terms in the Supplementary Material and cite the PRISMA statement by Moher et al (2009) as the basis for our work. We are happy to pull it back into the main manuscript, but this could bring us above the word limit .

Overall, I found the manuscript to be rather dry and perhaps insufficiently linked with the real-world applications that it refers to. For me it remains unclear reading this why practitioners should be looking into a multi-step decision making process as you suggest, even if you implicitly criticise those publications as being academic rather than conservation practice applied. In many places it reads like a -the process of decision making is imperfect- manuscript which is useful but hardly surprising or exciting for a practitioner.

We believe that by providing evidence of the many negative consequences that have been documented and linked to missing key decision elements during the planning in the introduction, and providing quantitative evidence of which framework is more often than others missing particular steps, we equip practitioners with information that allows for additional scrutiny and awareness during the planning with any of the frameworks. Knowing what is often forgotten helps to pay extra attention and avoid making the same mistake as others.

I also found the use of the "five element" quite difficult to follow given that you only refer to those elements once in the introduction and then use only this syntagm to refer to them throughout the entire results section (including figures) without much referring to their meaning. I also did not find the figures to be particularly useful from that point of view. I appreciate it would be additional work but perhaps a more detailed breaking down of the various elements by types of publications might be more insightful as well as some kind of re-stating those so that they are at hand when interpreting the results.

We hope the examples we added after reviewer comments from Conservation Biology have improved clarity.

The text is well written but needs a bit of polishing as there are small things to edit (e.g. line 431).

We replaced the second "Overall" with "Total" and have given the full text another careful read. We have tracked changes of all edits.

I agree with the conclusions but again, they are fairly bland and general.

We are glad to hear the reviewer agrees with the conclusions.

Some detailed comments:

Line 37- This seems to be an important justification of the study but I find it vague and unsupported. There are many conservation examples where the actions and strategies were effective but were implemented at insufficient scale to significantly alter the status of the threatened population. See for instance Schmidt et al. 2019 Biol.Cons. They can also be both at insufficient scale and implemented with adequate resources. Threatened species have very different scales of occupied habitat and thus the scale of required implementation can vary immensely. I suggest you detail and qualify this statement.

We believe what we have written reflects exactly what the reviewer mentions. We have added “to which extent” to the sentence to make clearer that we do not mean a binary classification of good vs bad decisions, but a scale with multiple important aspects.

Line 69- conservation publications is too vague. Presumably decision making processes in conservation publications or similar.

We have been trying to stay under word limit and have therefore settled in some cases on a brief description instead of a detailed one. We are happy to use more detailed descriptions throughout, if the word limit is not an issue, and have changed the phrase to “published descriptions of conservation focused decision processes”.

Line 67-74 Perhaps refer here and draw parallels to the biodiversity conservation goals from Maron et al. 2021 since you already mention them.

We would have loved to draw more direct links between Maron et al. and our work, however, while the subject is very similar, they write about very different aspects, so a direct link is very hard to create, apart from backing up the call for more rigour in decision making processes with a reference.

Line 80- minor point but you could cite a more up to date versions of the project rather than from 5 years ago

We are glad that got brought to our attention, we added the 2020 version of Sutherland et al. to the references.

Line 108- you should provide more methodological details here on the protocol in line with recommended practice. Extraction protocol checks, double verifications, etc.

We have provided a full description of our search protocol in the Supplementary Material, as well as a table with details on the number of publications filtered through the extraction and screening process, and full detail of the coding scheme. We also have described the rationale for our search and the judgment on fitting context of a focus on biodiversity conservation. Even thought we did not have the means to employ multiple people with the main extraction task of studies (this review was done as part of a PhD project without additional funding available), we went to great length and effort to test the classification protocol, with an investment of AUD 10.000 and multiple people working over more than 6 months together to meet and discuss judgments. We believe this exceeds the effort made in many published systematic reviews and are not sure what else to provide on top of that.

The comment might be another consequence of not having had access to the Supplementary Material. We believe although important, the amount of detail would be too much to include in the main body of text, hence our decision to provide it in the Supplementary Material.

Line 136 – why only 25? It is well below the recommended 10% proposed by others for extraction verification.

Our protocol for verification of the produced data was extensive in terms of time and budget, and we believe that this justified a smaller than usual sample. We added a description to the Supplementary Material: Three raters were in the mid or end phase of their Bachelor degree, and one rater was in in the final stages of his Master degree. Available funds (~AUD 10.000) were used as a primary stopping rule and all raters were paid for individual coding and discussions with a standard hourly rate until the money was used up. The moderate sample size of 25 papers is justified as a reasonable sample in light of budget and time constraints (Simmons, Nelson, and Simonsohn 2011).

Line 297 – but such failing are inherently implied rather than demonstrated given that you assume them from the failure to consider or report the inclusion of the various elements?

That is correct. There is no way we could prove that elements were not used, as we can only extract from the text what is reported. So we can quantify how often elements were reported, and discuss if large differences in reporting between frameworks might indicate that these elements might likely be also less often used. Our intention is to raise awareness, that people who are using these frameworks are at least conscious that they create the impression that elements were not used, when they do not include them in their reporting. The discussion explicitly states in line 501: "There is a range of potential scenarios in which the use of all elements may not be necessary or possible. For example, we could not assess if conservation scientists used key elements but did not adequately describe the details, or presented them only in supplementary materials."

Line 318 agreed but it does not mean such threats will not arise in future years

We strongly believe that future potential and not well understood threats should always have a lower priority in conservation planning than already existing, pressing and well understood threats. Of course, we agree that everything can always change rapidly, in which case priorities will (hopefully) change.

Line 377 see also Tamano et al. 2021 in PlosBiology showing the very unequal distribution of non-English conservation literature across the globe as well as possible solutions

Thank you for the suggestion, we have added Tamano et al and Hannah et al. to the reference of Konno et al in line 484.

Line 458-461 I am not sure what you mean here. Scientific literature is rarely considered as a whole, as you have as part of a quantitative review but there are numerous individual examples that fit the aims and scope of providing guidance on decision-making.

We completely agree with this, this was exactly the motivation for our review – to provide some overview on how elements of decision making are described in different decision-aiding frameworks and tools, to inform people who most likely look at/for few papers and hope they can use them as guidance. Knowing that many AM papers do describe much less often specific elements than other frameworks, and it is not guaranteed that any random AM paper lives up to the potential of the framework. It will take extra care to find quality examples, and this is an important insight and caveat for anyone who uses references to inform their own work.

We explicitly stated in the results and discussion that great examples exist for all frameworks, but the frequency of description makes it more or less likely to end up with one of these when searching for any publication with a specific framework.

Conservation Letters: Response of editor and comments of reviewers

Please note that some of the responses and edits in the following section have been made obsolete after edits based on the subsequent review for Conservation Biology (above section)

Editor's comments

20-Apr-2021

Dear Ms Beher:

Thank you for the recent submission of your manuscript entitled "10 years of decision-making for biodiversity conservation actions: A quantitative literature review on objectives, trade-offs, constraints and confidence as pathway to improving decision-processes" (CONL-21-0039) to Conservation Letters.

You can see that we've been able to secure two excellent reviews, and they agree that the manuscript isn't ready for publication. They raise three important issues:

First, the paper is quite hard to read. There are errors (typographic & grammatical) throughout the text. The figures and tables have no captions. The language is often definitionally loose. And the writing can be very hard to read, and needs a strong revision for readability.

We have rewritten large parts of introduction and discussion to tighten up the language and increase readability.

Second, the framing of the paper is largely around "outcomes", but the analysis is mainly about "process". I realise that the authors recognise this (they mention it specifically in the discussion), but there is ambiguity throughout the paper. The first reviewer recommends (and I concur) that the article could be reframed as a analysis of whether decisions follow best-practice processes, and leave the issue about whether this improves outcomes for another analysis.

We always intended to focus on the process, however, based on the well-founded assumption that robust processes increase the chance of good outcomes. We have clarified some sections to avoid creating the impression that robust processes guarantee good outcomes.

For example, line 49ff

Recent publications call for more attention to fundamental principles in conservation plans to increase the chances to achieve needed conservation outcomes (Maron et al. 2021; Leclère et al. 2020). A quantitative assessment of current decision-making for conservation actions can identify the level of uptake of important criteria from decision science, which is the basis for discussing possible ways to improve particular types of planning.

For example, line 109ff

The focus on five criteria that have been identified as particularly crucial (Carwardine et al. 2019; Wilson et al. 2006) provides the opportunity to evaluate current decision-making practices in the field of conservation and discuss implications.

For example, line 182 (rewording of heading to focus on process and not outcome)

1.2 An assessment of the level of uptake of five important criteria in conservation related decision-making processes

Third, the methods may have problems. One referee looked at a few of the papers and disagrees with your classifications. I had a quick look at one of the articles, and I agree with their conclusion. That's a real problem. I realise that flexible and accurate categorisation criteria (and categories themselves) are difficult to create, but unless a diverse readership can come to the same conclusions as you did, the results will not be useful or credible.

We acknowledge that we have not described in enough detail how categories were determined. We have added detail to explain some of the decision rules, as we can see how some papers can seem to be misclassified when not being aware of the precise rules, particularly around trade-offs. As trade-offs were often mentioned, but not integrated in the decision process, we decided to have a clear presence absence rule of a trade-off WITHIN the decision process instead of having to make a judgement of how much of a mentioning of trade-offs is enough to classify as present. One of the papers you mention (Koehn et al), is all about trade-offs, but does not come to a final conclusion, and was therefore classified as not including a trade-off. On the other hand, Chades et al is using a cost/benefit comparison to come to final conclusion, and is therefore classified as present. We did not differentiate between cost and other environmental, social or economic objectives for trade-offs, any weighing of different objectives against each other was considered a trade-off. We also included additional detail on the difficulties of linguistic categories and agreement on written context, as some readers might not be aware that disagreement when judgment is involved can be surprisingly common among highly trained experts. We agree it would be most important to create categories that would allow a wide readership to come to the same conclusions, however, believe that is a difficult task, and our strict rules that minimised subjective judgments should provide clear instructions, albeit can't avoid the fact that some disagreement on details is to be expected.

Specific changes include:

More detail on rules in Table 2 and following description (line 224ff)

3) Socio-economic considerations Are socio-economic objectives included?

Only examples that included a specific objective regarding social or economic factors that were considered in the choice between options were classified as "socio-economic objectives present"

5) Trade-offs Are trade-offs between different objectives described and explored?

Only examples that used trade-offs to make a final choice between options were classified as "trade-off present"

It is unfortunately common that even highly trained experts frequently come to different conclusions when faced with the same evidence (Kahneman et al. 2021). Unwanted variability in judgments can have a greater impact than biases, but is much less studied. This so-called "noise" is therefore to be expected when classifying text, and can be explored through quantifying variability

Additional detail in the discussion line 537 ff

The classification of text is not a trivial task, as different judgment on the same issues is common among experts (Kahneman et al. 2021). Making a judgment on the use of a specific criteria can be difficult. For example one publication (Koehn and Todd 2012) focus on the importance of trade-offs in the text, and describe it with theoretical examples, but do not use it for a final decision, while a second text (Chades et al) mentions trade-offs only briefly, but presents a figure that shows that they based their choice of action on information from a trade-off analysis in form of a cost-benefit curve. To avoid judgments based on feeling, for example if the subject has been given enough room, we decided to code a trade-off only as present when it was clearly used for a final choice of action. This is a clearer condition, as it does not need subjective judgment on how much description is enough, and where to draw the line when trade-offs are described, but not used. In general, we were only able to classify written content, and in many cases criteria might have played a role in the decision, but were not described in the publication.

If you can deal with these concerns, I would like to offer you the option of transferring your manuscript to the Society for Conservation Biology's new Open Access journal, Conservation Science and Practice. Choosing to have your manuscript transferred to Conservation Science and Practice has two advantages. First, it will remain under consideration within the Society for Conservation Biology family of journals. No reformatting will be required and any reviews already completed will be transferred with the manuscript, meaning that you may be given the option of revising and re-submitting based on current reviews. Transferred manuscripts will be assigned a handling editor from Conservation Science and Practice who will receive all prior manuscript correspondence. Manuscripts with decisions prior to review will be examined by a handling editor to determine the suitability to Conservation Science and Practice. However, Conservation Science and Practice is committed to a sound science model of publication where all studies reviewed as scientifically sound will be accepted for publication, irrespective of perceived generality or novelty of approach. Please let me know if you would like us to transfer your manuscript to Conservation Science and Practice. Alternatively, you can email the editor-in-chief of Conservation Science and Practice, Mark W. Schwartz directly (mwschwartz@ucdavis.edu).

Thank you for considering Conservation Letters for the publication of your study. The journal welcomes the submission of future manuscripts from you and your colleagues.

Sincerely,

Michael Bode, Senior Associate Editor

School of Mathematical Sciences

Queensland University of Technology

Brisbane, Queensland, Australia

Reviewer 1

Comments to the Author

This paper provides a systematic review of how comprehensively key decision analysis criteria are used in published conservation prioritisation studies. I agree that academic literature should be leading by example in terms of including the right decision criteria. The paper could be useful, but in its current form it fails on a few points.

First the paper is not easily readable, there are some inconsistencies in terminology and some unscientific ways of describing methods and outcomes. There are many missing words in sentences and mis-used tenses. The paper needs a thorough edit. A few examples of problematic language are below but this is not comprehensive.

- The title doesn't read well – should it be "as a pathway"?

We have changed the title to include all five criteria, and deleted the part that implies that improvement is necessary in general, to address some reviewer concerns. We hope the new title is also free of grammatical issues.

10 years of decision-making for biodiversity conservation actions: A quantitative literature review on objectives, trade-offs, threats, constraints and confidence

- When "context" is used it should probably be contexts, since each paper is a single context and its used to describe multiple contexts. Or say "a context" for singular. E.g. "Systematic Conservation Planning in academic context" – should be "contexts" or "in an academic context".

We have changed context to plural, or added an article, apologies for the mistake, the English and German grammar indeed have some differences.

- "… what also points to persisting threats that are not mitigated under the implemented management." Please rewrite this one and others with similar grammatical issues

We have reworded the sentence [line 144] to

"These examples highlight the importance of including explicit assumptions about the link between threats and actions in planning documents to enable evaluations of success and failure (Pressey, Weeks, and Gurney 2017)."

- When talking about potential pitfalls, phrases like "not thinking about" "not spending enough time" "nobody has tried to" are not scientifically appropriate ways of describing the situation. It isn't about the amount of time, or the lack of thinking, or trying – it is about whether the criteria is adequately incorporated into the problem framing.

We have rephrased the sentence to omit potential reasons for omitting specific criteria and instead focus on the absence of the criteria alone [line 72].:

“Examples include failing to identify meaningful objectives (Bond, Carlson, and Keeney 2008; Game, Kareiva, and Possingham 2013), missing links between actions and threats (Kuempel et al. 2019), not including constraints like costs or feasibility (Symes et al. 2016), or not conducting a sensitivity analysis (Runge et al. 2016; Larson et al. 2016; Sutton and Armsworth 2014; Mazor et al. 2014).”

- “Combined presence of criteria was much less frequent…” Not sure how this is true, since almost all the papers combined some criteria?

Thank you for bringing to our attention that this wording is not clear enough to understand what we aim to communicate. We have rephrased the sentence [line 249] to: ”The more criteria were combined, the less examples were found”.

- "If conservation science wants to improve and inform robust conservation management, decision-science has to be taken more seriously..." (personifying the field of conservation science, does not read well)

Thank you for this suggestion, we have changed the wording (line 581) to

If conservation scientists and practitioners want their publications to improve and inform robust conservation management, decision-science has to be taken more seriously,

- "In the end, all we can control is the planning..." (disagree, all this needs to be integrated with on-ground efforts and not done in silos… and this is an odd way of putting things)

We have rephrased this sentence to be clearer that we understand the planning process as a driving force of management, not a separate process. We do however believe strongly that effective management will benefit from a robust planning process that considers costs, impact on society/economy, uncertainty, and a clear conceptual model on how the management action will produce a positive outcome for conservation. If these criteria are not anticipated in the planning, they will certainly have to be considered when plans get implemented by staff on ground [line 589].

"A comprehensive plan that creates feasible and realistic strategies on how to implement management actions on the ground can minimize the risk of failure by including key criteria. Robust decision processes should be of high priority when time and budgets are as limited as in the effort of conserving our fast disappearing natural heritage on this planet."

- Why are there so many truncated titles of papers in the SI table, yet some seem to have the full title included?

We apologise for the truncated titles, however, this is unfortunately the way the results get exported by Web of Science. We believe the provided format is, although not pretty, enough to enable readers to identify publications. Cleaning up the list would require to open every publication and copy-pasting and formatting the title, which would be very time consuming and not provide any benefit to the reader. However, it is deemed to be a criteria for publication, we can invest the required hours.

Third, the scope of the paper and its conclusions are not clear or interpreted with enough depth to improve the field of conservation prioritisation.

- Decision science is actually the science of how people do and should make decisions. The paper is focusing on one part of decision science which is ideal structuring of decisions for analysis. Presumably the paper is focusing on prioritisation (ie when decision need to be made amongst a range of potential options), rather than planning (what is needed to manage all assets), but this isn't clear. The terms conservation planning, conservation management, conservation decision making are used interchangeably, to mean the same thing. The people who are undertaking these studies are not doing decision making, but decision analysis.

We apologise for not having provided enough description to communicate our approach in a clear way. We have added some detail to explain that our literature search was explicitly targeting detailed descriptions of how a decision was made in a conservation context, no matter if a case study in an academic context that tried to show how decisions should be made in general, or in a real world context that only wanted to document one particular process. We also changed wording throughout to make clear that we refer to decision-making as the specific part of a planning process in which actions get prioritised among options.

Line 194

This review used a systematic review protocol (Moher et al. 2009) through a keyword search of the Web of Science targeting literature published between 2009 and 2018 with the aim to identify descriptions of planning processes that aim to decide on a management strategy that seems most suitable to addresses a specific environmental problem.

We also have added detail in our definition of decisions (as choices between available options, informed by the evaluation of evidence in a planning process).

Line 71

Decision-making is the act of making an informed choice between available options, based on the evaluation of available evidence in a planning process.

- I was unable to locate table and figure captions. A useful figure to add would be one that shows the different kinds of conservation decision problems, and which ones tended to include each of the criteria – not just the % of criteria they include. Have things improved over time, e.g. based on the dates of the publications?

We apologise that the captions got lost in the process, we have added them in again.

Finally, I did a couple of quick checks on the analysis for a few papers I am familiar with and not sure the analysis is getting it right. Could these be checked? It is important to get these right or the very scientists you will be seeking to cite this work and use its recommendations would be put off.

Thank you for bringing to our attention that we have not provided enough detail around our coding procedure. Please see our response to comment #2 on the first page

A criteria was coded as present if:

1) objectives: clearly stated as objective and described how it is used in decision process

2) link between action and threat: By management of what type of threat is the objective achieved? example PA: explicitly stated in which way the PA is creating impact (over mitigating a particular threat) avoid mistake to assume MPA would protect from pollution, or PA would protect from invasive species or climate change

3) socio-economic consideration: included as objective and considered within the described decision process, not before or after decision/outside of paper

4) trade-off: trade-off not only mentioned or explained how to do it, but actually used to commit to and explain a choice (this is a conservative coding, as this leaves out all studies that explain how a trade-off can be made, without actually making a final commitment to a particular option)

- In the abstract point 2 is about linking an action to a benefit, but in the analysis this criterion switches to being focused on the action abating a threat. I find the threat criteria weaker – first because papers like Venter et al. come up as not having linked action to threat, yet they are expanding PA's which would protect places from habitat loss. Secondly, it is legitimate to have an objective that focuses on creating a benefit, rather than abating a threat (although admittedly usually this is through abating a threat, it doesn't always need to be articulated this way).

Thank you for bringing this up – we acknowledge that we need to add more detail in the text to clarify under which conditions assumptions on benefits without including specific threats is a problem, and when not. The reason we tracked not only envisioned benefits (stated as quantifiable objective) but also threats, stems from the known shortcomings of many planning protocols and implemented management actions. Particularly in protected area planning the blanket assumption that including a parcel of land in a protected area will deliver benefits is highly contested, as many examples have shown, from lack of management to the fact that often land is gazetted as protected that is not threatened from clearing as it is for example very high and steep or of poor soil quality, to many restoration projects that fail due to existing threats that would need to be addressed for any restoration efforts to be successful etc. We have added references that discuss these problems, as well as additional text. See for example:

Line 131

Decision makers must be able to justify, through assumptions of cause and effect, how they expect their chosen action to create the expected benefit.

Line 146

In addition, there is a general bias in the location of protected areas towards sites that are not threatened by land conversion (Joppa & Pfaff 2009). These examples highlight the importance of including explicit assumptions about the link between threats and actions in planning documents to enable not only meaningful outcomes but also evaluations of success and failure (Pressey, Weeks, and Gurney 2017).

Line 491

Still, although it has been shown that the locations of protected areas are biased towards places that do not face a threat of land conversion over ten years ago (Joppa and Pfaff 2009), it is still not common practice to include a clear description of threats in systematic conservation planning.

- The trade-off criterion appears a bit problematic too. To my understanding trade-offs are considered by Koehn et al and Donoso et al. – in fact it is the entire focus of the paper. Trade-offs not considered by Chades et al other than the cost vs benefit trade-off – this so not a multiple benefit trade-off, which seemed to be what the authors were looking for.

We apologise for not having provided enough detail to fully understand the coding rules. We have added more text as well as used Koehn and Chades as examples to explain how the coding rules work. We also added a section in the discussion, as our coding rules are likely to result in conservative estimates of the use of trade-offs. However, we do believe that clear coding rules that reduce subjective judgment as much as possible are most important. See also response to comments in line [309 ff and 826 ff] in this response letter.

- I am also not convinced on the criteria for academic vs real world - the PTM papers addressed are split between these categories but having been involved with all these studies, the designated categories do not reflect any real difference between them. In any case the term 'real world' is generous… maybe the categories should be "academic", "applied" and "implemented"?

Thank you for your comment. We started with four categories (scientific academic, applied academic, suggested, implemented), and collapsed them into two categories (academic and real-world (now conservation practice)) based on low agreement with the other raters in our reproducibility test. We acknowledge that more explanation is needed and have added a section in the discussion. As with all coding rules, we preferred with a hard and clear line of an explicit statement (that a plan was either in collaboration with a management authority or had been already implemented) to minimise subjective judgment and interpretation by raters. We are aware that the published texts won't always capture the true context, as authors might not be aware that detailed description of the level of implementation is important, so the description won't always match up with the actual story.

Line 555

In general, we were only able to classify written content, and in many cases criteria might have played a role in the decision, but were not described in the publication.

Reviewer 2

Comments to the Author

The manuscript "10 years of decision-making for biodiversity conservation actions: A quantitative literature review on objectives, trade-offs, constraints and confidence as pathway to improving decision-processes" takes a systematic quantitative literature review approach to catalogue and analyse peer reviewed and grey literature conservation planning processes. Broadly the database and the potential questions that can be asked are rigorous and high value. However, I am not convinced the right questions are being asked of this data or that the conclusions are supported by the data. The findings largely make sense but are not all unexpected. Essentially the findings support a broad conclusion that processes are being used in the contexts they were originally designed for in ways that match the process steps as broadly described and supported. For example the authors find that systematic conservation planning is broadly used for spatial design of protected areas and that SCP rarely includes threat-action links. This makes sense – SCP was designed to support spatial prioritization of protection.

And threat-action links are not included by design because there is a sound basis and belief that habitat loss is the primary threat and that protected areas broadly stop this.

We have added a section in the intro/discussion to elaborate under which conditions a missing link between action and threat can become a problem (see reply to reviewer comment in line [222].

Similarly the authors finds that adaptive management and structured decision making are commonly used for species management and threat abatement – contexts that these two processes were largely designed to directly address. Structured decision making tends to include all five criteria the authors recorded and this matches the steps ascribed in this process. The authors find adaptive management less frequently includes socio-economic considerations, but I strongly suspect this is a residual of how they have recorded socio-economic considerations and how common approaches to adaptive management such as the Open standards are built to consider humans. Humans and socio-economic considerations are embedded in the process rather than a singular criteria that might be discussed or quantified.

We agree with the reviewer that many reasons can lead to the situation that socio-economic factors are not reported in publications. However, we strongly believe that it is worth evaluating how frequently publications report on having used explicit socio-economic objectives in the planning, and if the frequent lack of reporting – regardless if constraints have been considered but were not reported, or constraints were really not considered in the planning – is a problem as it creates the IMPRESSION that socio-economic constraints are not important, or not worth reporting. If these criteria play a role when these frameworks are used, but are invisible in the published literature, can the literature be considered a good place to look for examples to inform decisions?

[…]

I give these examples as obvious ones where looking at the results I went yep that's about right, but also yep, but not sure about the 'so what'. And in the discussion, I disagreed with the authors inferences around needing to have all five criteria in all processes to make them 'best practice'. They've neglected to think through fit for purpose and context as well as whether the literature and real world even supports that having all five criteria is a sensible measure of process quality. Solutions to these shortcomings could be to revise the framing (primarily a major revision of introduction and discussion),

We acknowledge that our framing around "best practice" might have been too bold, we have changed the language and wording around the objectives of the review – our main aim is to illuminate how often these important elements of decision-making are reported, and discuss if the lack of them in the literature are likely to cause problems.

[…]

or to ask other questions of the data (which could be very fruitful but would require more work from the authors).

Detailed comments on these two options are provided below:

- Framing– The authors broadly (and fairly boldly) suggests that lack of outcomes is related to planning processes. However their references are theoretical in nature with no applied papers that have demonstrated that shortfalls in on ground outcomes relate to a lack of particular criteria or steps within a planning process. The framing also conflates issues of why a planning process may result in outcomes – 1) that a best practice planning process is more likely to result in implementation of conservation actions,

2) that best practice planning process is more likely to result in high impact conservation actions. Both are plausible (although I doubt either is supported by academic studies as only a handful of studies have interrogated the relationship between planning processes and actual outcomes) but they are conflated in a simplistic statement that a planning process should have all five criteria the authors have identified and that by doing so they will result in better outcomes.

We apologise to have created the impression that we believe good decision-making process guarantees good outcomes. Our intention was to argue that good process increases the chance to achieve good outcomes. The field of decision science exists based on the well-proven assumption that robust procedures make in general a difference to outcomes. We have clarified this in the following sections:

[…]

- Choice of five criteria – each criteria independently makes sense as a useful step in many (but arguably not all) contexts.

We acknowledge that there are always exemptions when the context makes the use of specific criteria difficult or impossible, we do however believe strongly that insights from decision science that informs decisions in business, medicine, military and other parts of society do also apply to conservation decisions. The decision elements we evaluate are well established to play an important role within prioritisation processes. They are also reflected in the step-wise approach of most frameworks we consider.

But not even the references the authors have used have been so bold as to say all five must be in all processes and that the absence of a particular criteria means a process is flawed or not best practice.

We have changed the language to describe the presence and absence of criteria with less judgment, see also reply to comment above in line

[…]

The criteria are largely theoretical, discussed in the literature independently and most have been suggested long after the planning processes were developed and described so inclusion of these types of criteria will be ad hoc in nature and fluid depending on context because they are not hard wired into the planning process steps as designed. As such it’s not reasonable to expect all five to appear in good or even best practice style plans.

Thank you very much for your question – the fact that many frameworks have been around for longer than the insight from decision science on how to incorporate specific criteria was one of the motivational factors that sparked this study. We strongly believe that it is important to evaluate how different frameworks fare in terms of these important criteria and discuss if the lack of description (or even use) might be a problem. We included a sentence in the introduction to make this clearer, and also reframed our wording of the main question to reduce judgment and just focus on how informative published examples of conservation decisions are on 5 different important decision criteria.

[…]

It's also likely that processes that have touched on each may not clearly articulate this in outward facing plan documents. For example trade-offs and socio economic considerations may well be part of the engagement process and decisions are made that acknowledge trade-offs but hugely unlikely that a plan would clearly articulate this in a public facing that that says who lost what or who won out. As an example

– the Great barrier reef re-zoning used a systematic conservation planning process and included humans throughout and clearly considered socio-economics but the papers don't always clearly articulate this as they focus on reporting how the biodiversity values were mapped and considered. The planning process also considered trade-offs amongst groups particularly through submissions and spatial revisions, but documents would never frame this as a trade-off analysis. The GBR is a gold standard process. It's not perfect but it's one of the best documented examples we have in the literature. But if I had to guess a priori the documents would have been assessed as having 2-3 criteria at best (no threat-action links, no trade-off analysis, probably no socioeconomic considerations).

Thank you for bringing up the GBR as an example. We strongly belief the GBR planning procedure was suffering of some of the issues we raise in the introduction. Despite being hailed as the gold standard, the zoning process left out important constraints, which were added afterwards and without tracing back the impacts on the quantitative objectives and metrics, and if these were still achieved. It is unfortunately a great example of how zoning can lead to weak outcomes in the end, and the point we want to make with the paper. When trade-offs are not transparently described, it is not possible to evaluate the plans for effectiveness. Unfortunately the GRB is also a great example for the fact that putting a protected area in place is by no means a guarantee that ecosystems are protected from decline.

We have added a short section in the discussion in line 341 of the manuscript. “The rezoning of the Great Barrier Reef is a famous example of this particular problem in protected area planning. Shortly after the plans had been made public, critical voices highlighted the limited benefits in terms of protection from threats to biodiversity, due to the spatial exclusion of industry-relevant areas (Devillers et al. 2015). While planning without a clear conceptual link between the intensity of threats in spatial planning units minimizes opportunity costs and facilitates implementation by reducing conflicts with resource users, protected areas become biased towards locations that are exposed to limited or no threats.”

- Questions to ask of the database - It’s reasonable to catalogue what processes considered what criteria but I believe a different question and framing of interpretation of the figures is needed. For example we can ask ‘did the expected criteria in each process based on their prescribed steps match what we found in practice’, ‘is there evidence that practitioners are choosing the right process for their context (eg based on guidance from Schwartz et al 2018 around choosing right process for questions being asked)’ or ‘is there evidence that including more of these criteria in the process leads to higher likelihood of implementation or better outcomes once implemented (not sure if the authors database recorded outcome variables to answer this but would be a very interesting question to ask if they did)

Thank you very much for suggesting alternative questions to ask of the database. We have followed you suggestion to reframe sections throughout the manuscript to step away from judgment and stick to evaluation of presence absence of criteria. Unfortunately we think answering the questions of the chosen processes are “right” for the context of the problem would require a much higher amount of subjective judgment, and a new set of criteria against which to measure the produced codes of “right’ or “wrong”. Attempts of matching out comes to processes have been made, but most failed due to lack of data, as we have cited in the introduction. As our database consists of descriptions of planning processes, not reports of monitoring after implementation, this questions is out of scope for us, although we agree it will stay one of the most important questions to try to answer.

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Appendix VI: Reviewers comments of “Decision-science navigates trade-offs between environmental and socio-economic objectives for marine debris mitigation”

Editor’s letter

Dear Mrs Beher

Manuscript PC24057, entitled 'Decision-science navigates trade-offs between environmental and socio-economic objectives for marine debris mitigation', which you submitted to Pacific Conservation Biology, has been reviewed. The comments of the reviewers and of the Associate Editor who handled the paper are appended below.

As you'll see, everyone is positive about your manuscript, while also making some recommendations as to how it could be improved. Therefore, I invite you to respond to the comments below and revise your manuscript.

In completing your revision, please note:

1. Should you disagree with any comment, please explain your reasons in the cover letter accompanying your revision.

2. Where further references are suggested, please check them carefully and add them if you feel that they are relevant. If you disagree with the relevance of the references, you are not obliged to cite them.

Thank you for submitting your manuscript to Pacific Conservation Biology; I look forward to receiving your revision. Instructions on how to revise your manuscript are included at the end of this letter.

Sincerely,

Dr Mike Calver
Editor, Pacific Conservation Biology
ali@theeditorialhub.com

Associate Editor's comments to author

Associate Editor
Comments to the Author:
We have now received two positive reviews for your manuscript. Both authors are generally quite positive about the quality and novelty of the manuscript, but have recommended minor revisions.

Reviewers' comments to author

Reviewer: 1

Comments to the Author
The topic of this manuscript is of high interest to scientists, policymakers, and coastal managers. The authors' research describes a social-ecological approach to improve site selection for marine debris interception & clean-up across a large geographic scope.

Below, I offer some specific comments and indicate potential areas for clarification.

Abstract/Introduction

Marine debris management can involve multiple actions at different points along the life-cycle of marine debris/plastic, i.e., from reduction in production to recycle/reuse/proper disposal to interception/clean up after debris has entered the environment. The management action focus of this manuscript is the removal of plastic debris before it flows into the seas (i.e., interception/clean-up). However, at points a reader may be confused as to the scope of actions being addressed in the paper. For clarity, I recommend providing examples of 'marine plastic mitigation' (Ln123) and ensuring terms are consistent throughout the manuscript.

Methods

Ln 153-165. The costs of removal were not included in the analysis, yet this is often a key deciding factor for feasibility of implementation. I suggest including an explanation as to why this was not a factor considered, as well as including this limitation (and implications on the decision outcomes) in the discussion (4.3 Constraints and uncertainty).

Ln 198-200. While using population density as a proxy for social value is reasonable, does this 'undervalue' less densely populated areas. How heavily weighted does population density end up being in the analysis?

Ln 307-309 and Ln 790-796. Unfortunately, the data on debris load in rivers is very limited for Southeast Asia. The only observational data from Asia used to calibrate the global river plastics input model developed in Lebreton et al. 2017 is from the Yangtze River. And these observational data are described as 'outliers'. The limitations of the modeled debris load in rivers from Lebreton et al. 2017 that underpins this study should be expanded upon.

Discussion.

Ln. 766-796. In addition to the other study limitations that I recommend addressing above, another limitation that may be mentioned is that the study did not integrate social values based on community input. For example, Bangladesh may hold a different habitat in higher value (e.g., mangroves) than China or other heavily coral-reliant societies. Inclusion of those other valued habitats would likely alter the ranking outcomes.

An assumption is that clean-up strategies are effective and can remove large fractions of debris. The effectiveness of a strategy will vary greatly depending on resources, physical conditions and the types and amounts of debris.

Reviewer 2

Comments to the Author

1. The methodology would benefit from more detailed explanations regarding the specific criteria used to rank different intervention sites. While the SDM framework is highlighted, it would be more insightful to include precise details on how stakeholders' preferences were quantified and the weight assigned to different factors. Additionally, the metrics of success for the selected interventions are not fully defined, making it difficult to gauge the long-term effectiveness of these strategies.

2. While the article provides a solid framework for addressing plastic pollution, it would benefit from including comparisons to similar frameworks or methodologies that have been employed in other regions. Specifically, the

authors should consider citing relevant studies that provide similar decision-making frameworks for plastic mitigation strategies, such as the following:
Marine Pollution Bulletin studies: https://doi.org/10.1016/j.marpolbul.2024.116853, https://doi.org/10.1016/j.marpolbul.2021.112258.
Ocean and Coastal Management:
https://doi.org/10.1016/j.ocecoaman.2024.107149.
Regional Studies in Marine Science: https://doi.org/10.1016/j.rsma.2024.103596.

These references will enhance the scientific rigor and situate the current study within the broader literature on marine debris mitigation.

3. The conclusion section could be condensed and made more precise. It currently reads as a repetition of the discussion points rather than a summary of key findings and policy recommendations. For example, the conclusion could more clearly articulate the practical applications of the SDM approach and provide direct recommendations for policymakers and local governments on how to prioritize sites for clean-up efforts.

General Recommendations:

Ensure that all sections, particularly the methods and results, are as detailed as possible to make the study more replicable.
Streamline the conclusion and focus on practical takeaways for policymakers and environmental managers

Appendix VII: Positionality Statement

I am of white European heritage and come from a middle-class family background in Germany, which brought a number of unearned privileges, such as free access to education, including university. My parents, as well as my elder brother, attended university before me, although I am the first biologist in the family, and the first family member to finish a PhD. I have worked in several countries as an environmental scientist after I graduated from university in Germany, and before commencing my PhD (Germany, Switzerland, Australia), mainly in international research groups, which have all shaped my understanding of and way of conducting research. I started learning English in school in Germany when I was 12 years old.

Appendix VIII: Published chapter 3, 4, and 5

Received: 26 April 2024 | Accepted: 26 May 2024

DOI: 10.1111/csp2.13170

REVIEW

Conservation Science and Practice
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10 years of decision-making for biodiversity conservation actions: A systematic literature review

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Funding information

John Hodgson Scholarship; Research Training Program Scholarship Australia

Abstract

Decision science emphasizes necessary elements required for robust decision-making. By incorporating decision science principles, frameworks, and tools, it has been demonstrated that decision-makers can increase the chances of achieving conservation aims. Setting measurable objectives, clearly documenting assumptions about the impact of available actions on a specific threat or problem, explicitly considering constraints, exploring and characterizing uncertainty, and structured deliberation on trade-offs have been identified as key elements of successful decision-making. We quantify the extent to which these five elements were utilized in published examples of decision making in conservation in both academic and conservation practice between 2009 and 2018. We found that less than 50% of identified examples included all five elements, with differences in the degree of decision science applied across five commonly used decision support approaches: adaptive management (AM), systematic conservation planning (SCP), structured decision making (SDM), multi-criteria decision analysis, and cost-effectiveness analysis. Example applications that utilized the SDM framework were limited in numbers but used on average more than 50% of the five key elements we considered. Although SCP and AM constituted the majority of examples, they were more prevalent in academic studies rather than management applications. SCP and AM examples were widespread in protected area planning, threat abatement, and restoration. Strong geographic bias exists in documented conservation activities that deploy all five decision science elements.

KEYWORDS

adaptive management, conservation planning, cost-effectiveness analysis, decision theory, multi-criteria decision analysis, structured decision making, systematic conservation planning

1 | INTRODUCTION

Despite the substantial effort and investment into the conservation of species and ecosystems, biodiversity loss is accelerating (C. N. Johnson et al., 2017). The list of threatened species keeps growing, with over a million species threatened by extinction, and many species expected to be lost within two decades (Díaz et al., 2019; WWF 2020). Global assessments have identified comparatively few successful management examples that led to the down-listing of species' extinction risk (Bolam et al., 2021; Hoffmann et al., 2010). Most national and international environmental strategies fall short of their nominal targets and many report worsening trajectories for monitored species (McDonald et al., 2015; Secretariat of the Convention on Biological Diversity, 2020; Tittensor et al., 2014). It is not possible to determine to which extent the strategies developed to stem biodiversity decline are flawed or sound, or whether they are implemented at too small a scale or with inadequate resources. If important insights from decision-science are neglected during planning, the risk of failure and the possibility of perverse or unintended consequences increases (Bode et al., 2015; Devillers et al., 2015; Game et al., 2013; Hervé et al., 2016; Renwick et al., 2015). Existing evidence across multiple disciplines including medicine and public policy including environmental policy shows that structured processes based on decision science lead to a better understanding of the problem at hand, sound evaluation of available options, and the trade-offs between them (Arvai et al., 2001; Bekker et al., 2003; Herek et al., 1987; Schafer & Crichlow, 2002). Principles of decision science have been used to assess other aspects of conservation applications, such as ecological indicators (Watermeyer et al., 2021). Recent publications call for greater attention to be given to fundamental principles in conservation plans to increase the chances of achieving urgently needed conservation outcomes (Adams et al., 2019; Kellon & Arvai, 2011; Leclère et al., 2020; Maron et al., 2021; Rose et al., 2019).

1.1 | Decision support approaches used in conservation

A range of decision support approaches and tools exist to guide conservation decisions (Acosta et al., 2016; Bower et al., 2018; Schwartz et al., 2018). Frequently used frameworks include systematic conservation planning (SCP), adaptive management (AM), and structured decision making (SDM), and frequently used stand-alone prioritization concepts include multi-criteria decision analysis (MCDA) and cost-effectiveness analysis (CE). These differ in key aspects (Table 1) due to their evolution and use in different contexts. Moreover, the use of any given framework or approach does not ensure that all of the key elements of sound decision-making are incorporated in any given decision (Game et al., 2013; Gregory et al., 2012; Kahneman & Tversky, 1984; Wilson et al., 2006; Wilson et al., 2007).

Each of the five commonly used options in Table 1 utilizes distinct steps in the decision-making stage of planning processes. These steps aim to ensure important elements are included to decrease the risk of not meeting objectives (Nicholson & Possingham, 2006). Most frameworks describe steps at a high level, such as defining objectives or developing alternatives. This recognizes that each decision context may require a tailored approach or tool to be used in each phase. While vagueness within decision support options provides flexibility to account for context, it can lead to unintended neglect of the key steps.

Based on fundamental decision theory texts in the context of conservation (Gregory et al., 2012), we identify

TABLE 1 Frameworks and prioritization concepts that are frequently used to support decisions for conservation management strategies.

Framework/ prioritization concept	Key aspects	Key reference
Systematic conservation planning	– Spatially explicit planning for protected areas – Map as output – Based on selection of distinct planning units	Margules and Pressey (2000); Moilanen et al. (2009)
Adaptive management	– Monitoring information used to adjust repeated decisions – Experimental set up – Learning about effect of management intended	Keith et al. (2011)
Structured decision making	– Importance on clarifying decision problem and eliciting appropriate objectives and metrics – Explicit comparison of alternatives – Often with transparent quantification of trade-offs	Gregory et al. (2012)
Multi-criteria decision analysis	– Focus on relative importance of different objectives – Scoring, weighting, and summation of different criteria and/or objectives to rank options	Adem Esmail and Geneletti (2018)
Cost-effectiveness analysis	Consideration of cost without compromising objectives other than cost: comparison based on return of investment	Wilson et al. (2009)

TABLE 2 Assessed categories that were classified within this literature review.

Five elements for robust decision-making	Classification (presence/absence)
Objectives	Are environmental objectives quantitatively expressed?
Actions and threats linked in a theory of change	Is there a clear link to a threatening process? Examples were classified based on Salafsky et al. (2008). As conservation actions aim in most cases to mitigate existing threats that cause a decline or deterioration, we focused on the inclusion of a specific threat as proof of an existing theory of change in the decision-making process.
Socioeconomic considerations	Are socioeconomic objectives included? Only examples that included a specific objective regarding social or economic factors that were considered in the choice between options were classified as "socioeconomic objectives present."
Sensitivity and uncertainty analyses	Are sensitivity or scenario analyses done to test for effects of uncertainty?
Trade-offs	Are trade-offs between different objectives described and explored? Only examples that used trade-offs to make a choice between options were classified as "trade-off present."
Four descriptive factors	**Multiple entries possible**
Decision support option	Five frameworks and prioritization strategies, or "mixed" if more than one was used (Table 1)
Context	If collaboration with management authorities or implementation were explicitly described: "conservation practice", if not: "academic"
Type of management	Five types of proposed management actions based on Salafsky et al. (2008)
Location	Country in which proposed management was located

five crucial elements of a robust decision process against which to evaluate published descriptions of conservation focused decision processes: (1) identify clear objectives, (2) identify measures of anticipated impacts of planned actions with a clear theory of change, (3) document financial and social constraints, (4) characterize uncertainties and conduct sensitivity or uncertainty analysis, and (5) characterize and measure trade-offs. Evidence of the importance of these five decision elements is discussed in more detail in Supplementary Material S1 in Data S1. The five critical elements of decision making that we highlight here have been highlighted as critical in decision-making among wildlife managers (Fuller et al., 2020).

1.2 | Evaluating decision processes in conservation

Recent studies that identify the factors leading to success and failure of decisions made in conservation management include strong recommendations for evidence-based conservation (Sutherland et al., 2020; Sutherland et al., 2004), the creation of data repositories (https://www.miradishare.org/ux/home, https://www.conservationevidence.com, https://marinescp.jcu.io), and reviews that provide an overview of conservation management effectiveness (Bayraktarov et al., 2016; Geldmann et al., 2018; McIntosh et al., 2018). Attempts to quantify the effectiveness of implemented conservation plans by measuring outcomes have largely failed to produce definitive findings due to mixed evidence (Edgar et al., 2014), data paucity (McIntosh et al., 2018), and high variability between conservation contexts (Lester et al., 2009). However, the importance of sound decision-making is widely accepted (Butt et al., 2020; Carwardine et al., 2019; Visconti & Joppa, 2015; Wilson et al., 2006). The damaging effects of neglecting elements of good decision-making during planning are well documented. Failure to identify meaningful objectives (Bond et al., 2008; Game et al., 2013), missing theory of change as link between actions and threats (Kuempel et al., 2019), failure to include constraints such as costs or feasibility (Symes et al., 2016), or failure to conduct sensitivity analysis to evaluate uncertainty (Larson et al., 2016; Mazor et al., 2014; Runge et al., 2016; Sutton & Armsworth, 2014) can lead to suboptimal or counterproductive decisions. A systematic assessment of decision-making for conservation actions can identify the degree to which the key elements of sound decision-making are being utilized in conservation planning and management.

Here we provide a comparative and quantitative review of the extent to which the elements of decision-making are utilized in published work on conservation decisions problems. Our review is based on 466 examples drawn from the peer-reviewed literature and provides insight into the types of conservation decisions that benefit from the application of all elements set out in decision theory. We discuss the elements of decision-making that might need to be bolstered to produce more robust conservation decisions and better outcomes.

2 | METHODS

2.1 | Data collection

We use a systematic review protocol (Moher et al., 2009) through a keyword search of the Web of Science, targeting literature published between 2009 and 2018. Our goal was to find documents describing decision-making that selects a strategy from a range of options to address a specific environmental problem. A search was conducted in December 2018, using the term "decision-making" and five common decision-aiding frameworks (Bower et al., 2018; Schwartz et al., 2018) and prioritization methods (Supplementary Material S2 in Data S1). Our search yielded 7106 publications, which were subsequently screened for a conservation-related decision-context, resulting in 1218 publications that were read in detail. Of these, 466 examples described a decision process of prioritizing management strategies in adequate detail to understand the decision process, and information on five decision elements and four descriptive factors was collected from each (Table 2). If a publication described examples of different decisions, each individual decision was recorded as one example (see, e.g., Canessa et al., 2016). If case-studies were referred to with citation, they were excluded to avoid redundancy. Horizon Scanning and Strategic Foresight (Cook et al., 2014) had been initially included in the search but were not part of the analysis as no example was found that described a conservation-related decision between available management options.

Table S3 in Data S1 provides full information on the coding scheme. All code and data are available on figshare (https://doi.org/10.6084/m9.figshare.17205713.v1).

2.2 | Reliability of data classification

Several measures were taken to improve clarity of categories and to identify errors and variation in the data classification. Extraction of qualitative information from text is not free from bias and errors (Marcoci et al., 2019; McHugh, 2012). It is common that highly trained experts come to different conclusions when faced with the same evidence (Kahneman et al., 2021). Such unwanted variability in judgments can have a greater impact than bias. This variability is to be expected when classifying text and can be explored by quantifying variability across multiple raters. We assessed the reliability of the extracted data using 25 examples (Supplementary Material S4 in Data S1). Percent agreement between four additional raters and the lead author was well above conventional thresholds of 75% for inter-rater-reliability-testing for all categories. The error rate of the main rater was lower than the additional raters.

3 | RESULTS

3.1 | A profile of conservation decisions

Our quantitative analysis included 466 examples (Tables S5 and S9 in Data S1). About a third of the 466 examples described either a collaboration with authorities that were interested in finding a solution to a particular conservation problem or partial or full implementation at the time of publishing (128 examples, referred to as "conservation practice" in the following). Two thirds (338 examples) have been conducted without any indication that decisions were implemented by a practitioner, manager, or agency (referred to as "academic" in the following). The numbers of examples for different decision support approaches were biased toward SCP (212) and AM (106), while all other, as well as mixed approaches, contributed 29–47 examples each (Figure 2, Table S5 in Data S1).

We found a clear difference in how often the five key decision elements were used overall and in combination. The description of only one of the elements was rare in both academic and conservation practice contexts. In academic contexts, the combination of three or four elements was more than twice as likely as the combination of two or five elements. In conservation practice contexts, numbers of examples that combined two, three, four, or five elements were similar (Figure 1). In total, less than half of all examples (211 examples: 52% of conservation practice and 37% of academic examples) used more than three of the important decision elements in combination. The relative frequency of examples with five elements was slightly higher in conservation practice contexts. When three elements were combined, trade-off, link to threat through a theory of change and socioeconomic constraints were more often missing than quantitative objectives or sensitivity analysis. When four elements were combined, 95 examples excluded trade-offs and 21 linking to a threat through a theory of change, while the other elements were less often missing. Only 27% of all examples explicitly documented deliberation on trade-offs. Each of the other elements was described in 70%–84% of examples.

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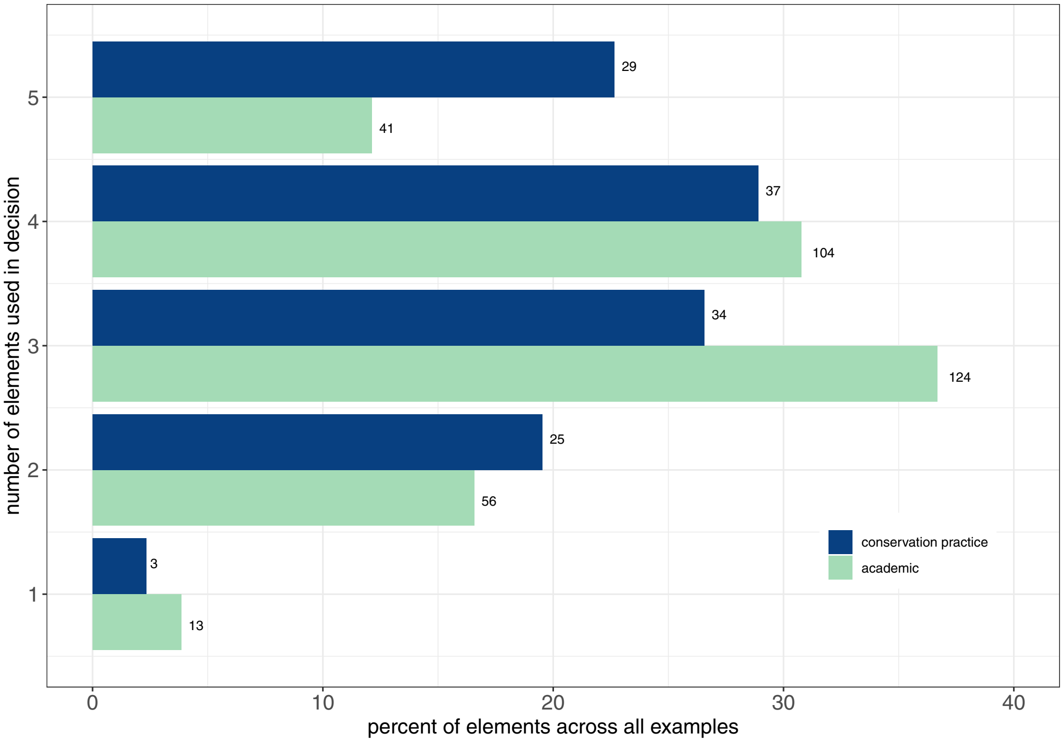

FIGURE 1 Number and proportion of key decision elements that are described in academic and conservation practice contexts.

We found clear differences when comparing how often specific decision support options were used in academic or conservation practice contexts and how often each used the five different elements (Figure 1 and Figure 2). AM was the most often used decision support approach in conservation practice contexts and the second most often used in academic contexts (Figure 2). Only a few of these examples used all five decision elements in combination, and a large fraction used only two or three elements. Quantitative objective and socioeconomic objectives were not described in approximately half of the academic and conservation practice examples.

SCP comprised the largest fraction of examples in academic studies (Figure 2a). Half of these examples did not describe a clear link to a threat through a theory of change, and a third did not include any socioeconomic objectives (Figure 2c). There were far fewer examples of SCP in conservation practice contexts, and in those examples, a relatively low proportion clearly described a theory of change that links management to a threat and conducted sensitivity analysis. In contrast, a higher proportion of applications considered documented socioeconomic objectives (Figure 2c). A higher fraction of SCP examples used five elements in conservation practice contexts than in academic contexts. At the same time, almost a quarter of the conservation practice examples for this framework used only one or two elements (Figure 2b).

SDM was the only framework that was used predominantly in a conservation practice setting (74%), while over 60% of examples of each of the other decision support strategies were set in an academic context (Figure 2a). Conservation practice examples of SDM had high inclusion rates for all elements. Academic examples of SDM included socioeconomic objectives less often (Figure 2c).

Compared to other decision support options, examples of MCDA rarely articulated a quantitative objective in both conservation practice and academic contexts. About a third of academic examples that used CE did not describe quantitative objectives for the biodiversity value that was supposed to benefit from the management, and a third of conservation practice examples that used CE did not describe any sensitivity analysis or other exploration of uncertainty.

SDM described all five elements in 28% of examples, compared to 24% of CE examples, 19% examples with mixed decision support, 15% of SCP examples, 12% of MCDA examples, and 7% of AM examples (Figure 2a). To account for the rare use of trade-offs, we tested a relaxed condition for including them, with similar results (Figure 2a). There was no visible temporal trend for the frequency of using four or five elements in any of the frameworks (Supplementary Material S6 in Data S1).

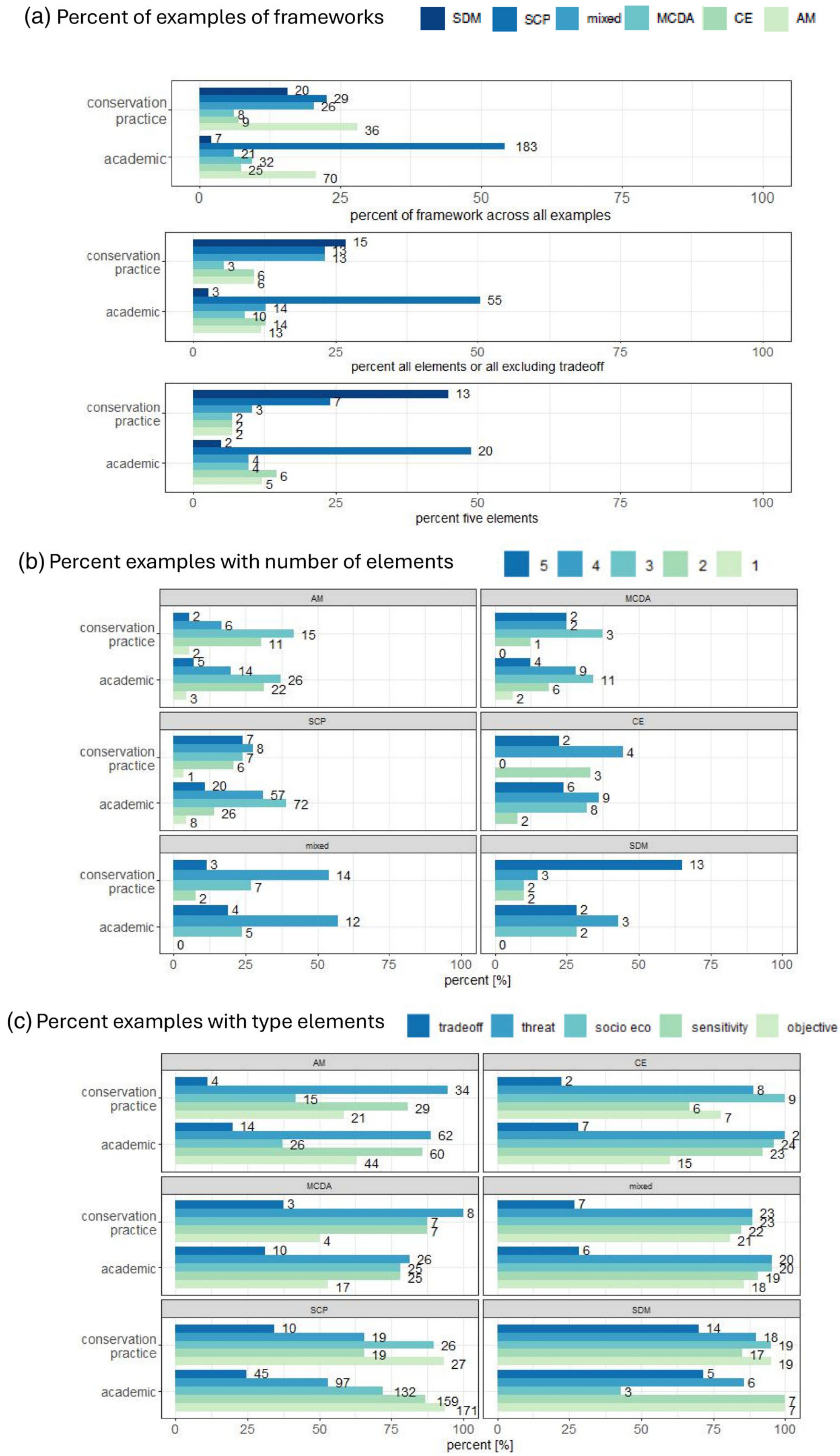

FIGURE 2 (a) The use of frameworks in conservation practice and academic contexts in general (top row) and in examples that use all elements (bottom row). The middle row shows the examples that use either all elements or exclude only trade-offs. The *x*-axis shows percent within each group of academic and conservation practice examples. Each bar is labeled with the number of examples. (b) The use of elements within each framework in conservation practice and academic contexts. The *x*-axis shows percent within each framework of academic and conservation practice examples. Each bar is labeled with the number of examples. (c) The use of specific elements within each framework in conservation practice and academic contexts. The *x*-axis shows percent within each framework of academic and conservation practice examples. Each bar is labeled with the number of examples.

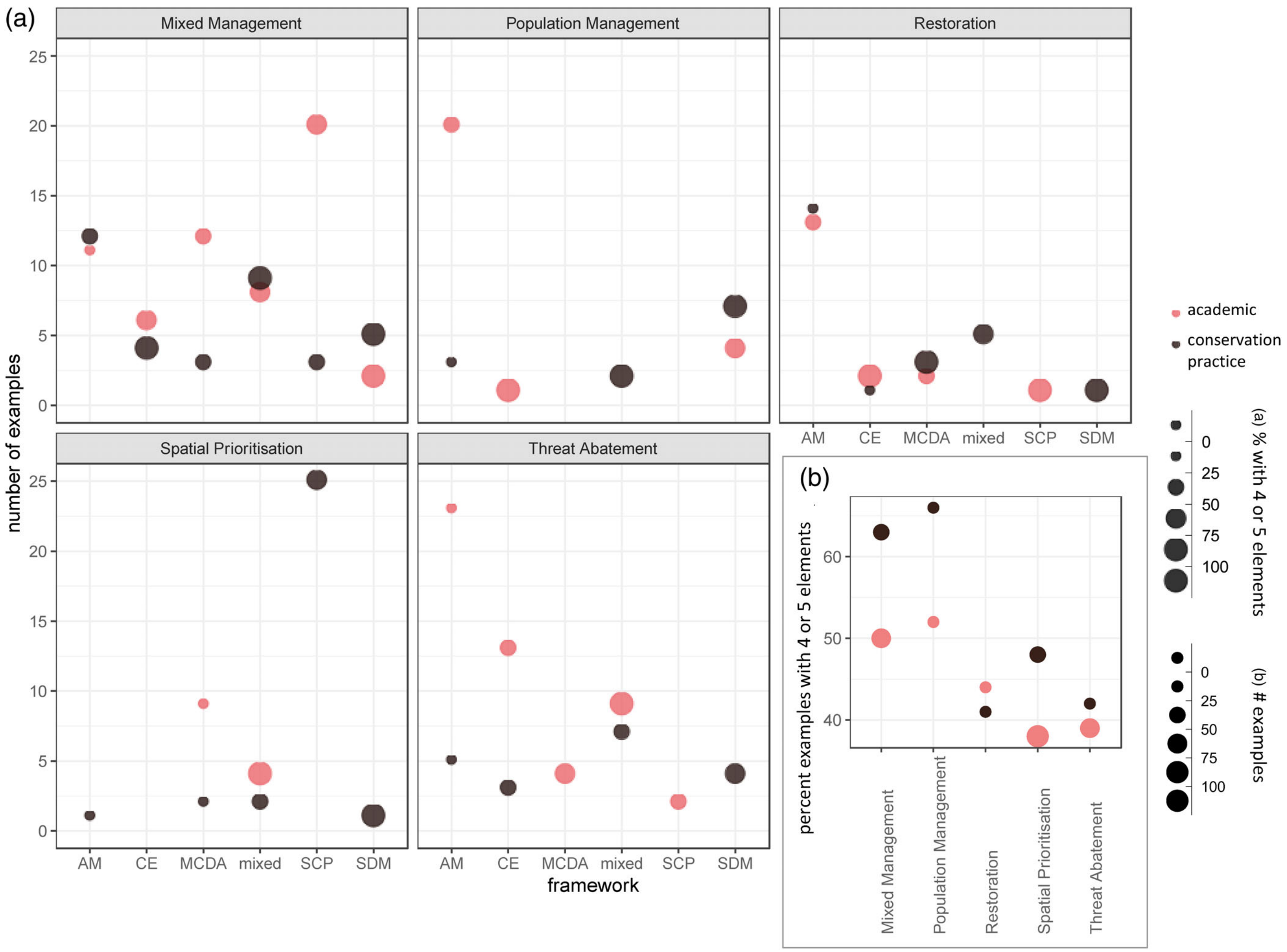

FIGURE 3 Panel (a): Bubble plot of how often different frameworks were used in academic and conservation practice examples for different types of management. The *y*-axis shows the number of examples, while the size of the points represents the fraction [%] that used four or five elements. Note that in order to visualize differences in the numbers along the *y*-axis, the high number of examples that use systematic conservation planning for spatial prioritization is only shown in panel (b). Panel (b): The frequency of using all five elements within different management types ranges from 38% to 66%, with spatial prioritization and threat abatement in academic contexts at the lower end and population management and mixed management in conservation practice context at the higher end.

3.2 | Application of all elements of decision-making within different types of conservation problems

Particular frameworks were preferred for specific types of conservation problems. Several patterns emerged in the analysis of how often more than three elements were included in each type of management in conservation practice and academic contexts (Figure 3).

Decisions were made most often within preselected management strategies (see different panels in Figure 3). Only about a quarter of all examples (95 out of 466) considered more than one management strategy in the decision-making process ("mixed" box in Figure 3a). The majority of examples considered options for one predetermined strategy exclusively (202 spatial prioritization [including protected area planning], 70 threat abatement, 42 restoration, and 27 population management). The most common mixed combinations were spatial prioritization and restoration (26 examples), threat abatement and population management (14 examples), and threat abatement and restoration (13 examples). Seventeen examples did not match the five management categories.

Some frameworks were found more often for a specific type of management than other frameworks (differences of height of bubbles in each panel): While examples for mixed management can be found for all frameworks, spatial prioritization was most often conducted with SCP, and most decisions on restoration were made within an AM framework.

Some frameworks were utilized differently in academic and conservation practice contexts (see difference in height for each color): mixed management examples in academic contexts used most often MCDA and SCP, but mixed management examples in conservation practice contexts used all other frameworks more often. Examples for population management and threat abatement in academic contexts used most often AM, while the same type of management in conservation practice contexts used frequently other frameworks.

Some types of management were particularly prone to decision-making with a low number of decision elements (smaller points that are higher up along the *y*-axis in each panel and lower points in plot 3b). For example, restoration and mixed management examples used AM often in both conservation practice and academic contexts, but these examples included four or five elements at a lower rate than MCDA or mixed approaches. Academic population management examples used most often AM, with a lower frequency of using four or five criteria than among the fewer examples of CE or SDM. Population management examples used mixed frameworks or SDM as often in conservation practice contexts as AM and included four or five elements more frequently. Panel b in Figure 3 shows that decision-making for threat abatement and restoration was more prone to omit two or more elements both in academic and conservation practice contexts, and spatial prioritization in academic examples used least often more than three of the key elements.

To be sure the likelihood of including all elements was influenced by specific decision support options and not driven by specific authors, particularly for decision support options with fewer examples, a coauthor network was created for all examples that used five elements. The network (Figure S7 in Data S1) shows a high diversity of authors in general for all decision support options, with one large network of authors of academic examples who are connected through the Centre of Excellence for Environmental Decisions in Australia.

3.3 | Geographic distribution of examples and use of decision elements

Although examples of conservation decisions existed for over 80 countries across all continents, the location of the examples was biased toward the United States and Australia. The two countries provided more than a third of all examples overall, as well as for academic and conservation practice contexts individually (Figure S8 in Data S1). Academic examples were found for 52 countries and conservation practice examples for 33 countries. However, there were only six countries with more than two conservation practice examples, and no conservation practice examples were found for most African, Middle Eastern, and Latin American countries.

4 | DISCUSSION

We have shown that robust conservation decisions according to standards of decision science exist across all decision support options in academic and applied contexts. But the bulk of academic and applied studies that document decisions that we evaluated in this study do not apply all of the key elements of decision science, or at least did not report them. We found differences in the use of decision elements between decision support tools in academic and applied contexts and across different management activities. Our results imply that problems that stem from omitting specific key elements, including risking further species' declines when the planning lacks quantitative and ecological meaningful objectives (Carwardine et al., 2009; Game et al., 2013; Pfab et al., 2011), implementing actions that do not address the key threats (Bayraktarov et al., 2016; Devillers et al., 2015), or creating socioeconomic problems when not acknowledging the human context during the planning (Bode et al., 2010; Wittemyer et al., 2008), are likely to be common across the conservation discipline.

Of the decision support frameworks we considered, SDM is the most recently developed framework, and therefore draws on the most complete suite of insights from decision science. Although applications of SDM most often included many elements, they were also the most underrepresented in our database and almost exclusively from the United States. We believe our results provide great insights into the potential shortcomings affecting decision-making and highlight opportunities for more transparent reporting of important decision elements in publications.

The type of decision support that was used during decision-making contributed more to the differences in the uptake of key elements than whether the activity was academic or applied. There were clear signs that some conservation management strategies are most likely to be at risk of failing to achieve ecologically meaningful benefits due to a propensity to omit key elements of the decision-making process.

4.1 | Consequences of limited consideration of decision elements in protected area planning

It has been shown over 10 years ago that the locations of protected areas are biased toward places that do not face a threat of land conversion (Joppa & Pfaff, 2009), and many publications have discussed the shortcomings of protected areas as a tool to protect biodiversity (Barnes et al., 2018; Cooke et al., 2023; Mora & Sale, 2011; Naumann et al., 2021; Pressey et al., 2017). These discussions focus particularly on threatening processes, and if and how they are included in the planning. Our results show that it is still not common practice to include a clear description of key threats and the expected mechanism of mitigation in publications of SCP. Similar evidence has been published in an EU context (Hermoso et al., 2022).

If our results are representative of SCP in the real world, many of the protected areas could have limited potential to protect biodiversity from existing threats if they were implemented because lower opportunity costs cause a bias toward prioritizing areas with low or no threat pressure. The rezoning of the Great Barrier Reef is a famous example of this particular problem in protected area planning. Shortly after the plans had been made public, critical voices highlighted the limited benefits in terms of protection from threats to biodiversity, due to the spatial exclusion of commercial fishing areas (Devillers et al., 2015). While planning without a clear conceptual link between the intensity of threats in spatial planning units minimizes opportunity costs and facilitates implementation by reducing conflicts with resource users, protected areas become biased toward locations that are exposed to limited or no threats.

The low rate of socioeconomic objectives in academic studies could be explained by the focus on specific aspects with the aim to show novel approaches in SCP. However, the frequent lack of any sensitivity or scenario analysis in a third of applied examples indicates that addressing uncertainty is not widely considered when making decisions for a protected area. This may lead to conservation area designs that are susceptible to failure of key assumptions about, for example, the location of key species habitats, or how species may respond to changing climates (Moilanen et al., 2006).

4.2 | Consequences of limited use of the full potential of AM for threat abatement and restoration

The lack of quantitative objectives and socioeconomic objectives has been stated as one of the most common mistakes in conservation decision-making (Game et al., 2013). The fact that these key decision elements are often missing in documentation of AM might have broader implications for many restoration and threat abatement projects, as the clear majority of examples that we found for these management strategies used AM for decision support. If AM is primarily used to monitor changes in real-time and practices "learning by doing," often without clear ecological objectives (Carwardine et al., 2009), it is questionable if these projects have the capacity to deliver the intended conservation outcomes (Gregory et al., 2006; Riley & Gregory, 2012). An example from our survey is Briceno et al. who compare interventions against poaching for yellow shouldered parrots but do not provide any quantitative objective regarding the level that poaching needs to be reduced to keep the population at viable levels (Briceño-Linares et al., 2011). The lack of quantitative objectives was also common in decisions based on CE, where often only threats were targeted, without a clear measure of how a reduction of a threat would benefit a species or habitat. Examples included improving water quality to benefit waterfowl with no quantitative objective for the waterfowl (Martin-Ortega et al., 2015), sediment reduction for the Great Barrier Reef without any quantitative objective for reef-related biodiversity (Bouma et al., 2011), or control of an invasive species without a quantitative objective for biodiversity that would benefit from the control (F. A. Johnson et al., 2017). The plain fact that CE is a means to find the best ratio between costs and benefits might explain why targets were often not articulated in more detail, but it highlights how easily important elements of the decision process can get overlooked.

Developing effective AM plans is challenging, resulting in few success stories (Gregory et al., 2006; Riley & Gregory, 2012). Similar to our findings, a recent review of AM found few applied AM projects compared to academic studies (Westgate et al., 2013). The review also suggested that often decisions makers used the 'adaptive management' label when the actual approach did not meet the standards of the theory behind it. This may also explain the low number of described elements in our results (Figures 2 and 3).

Restoration attempts reportedly have a low success rate and often neglect socioeconomic criteria or considerations of threats in a theory of change (Bayraktarov et al., 2016; Suding, 2011; Wortley et al., 2013). Restoration is a key conservation activity worldwide and is fundamental to achieving global biodiversity framework goals (CBD, 2022; Fischer et al., 2021; Strassburg et al., 2020). A greater emphasis on a rigorous decision process, particularly under AM, seems to be a promising pathway to improve success rates.

4.3 | Different preferences of decision support options in applied versus academic examples

SCP and AM are not necessarily the most common decision-aiding support options in the conservation practice, despite their popularity within academic case studies. The dominance of these decision support options in academic contexts might obfuscate important other questions and problems that applied conservation managers are interested in. The misalignment might be partly caused by the ease with which some tools can be used to work on well-established and intellectually interesting problems, like the use of Marxan for the minimum-area/maximum-coverage in spatial planning, or the use of Bayesian-Belief-Systems and Value-of-Information in AM. The high proportion of SDM in conservation practice might be an indication of the usefulness of processes that are more closely linked to decision science in applied contexts.

4.4 | Spatial patterns in decision approaches

Examples in which all five critical elements of decision making were applied were strongly biased toward Australia and the United States. Recent literature reviews on biodiversity confirm the persisting bias in publications toward very few countries, which do not match with the distribution of biodiversity (Di Marco et al., 2017; Wilson et al., 2016). Data gaps in meta-analyses are likely not stemming from a lack of research, but rather from language barriers that prevent existing literature from being visible in major English online repositories (Amano et al., 2023; Amano et al., 2021; Hannah et al., 2024; Konno et al., 2020).

Efforts such as summaries for particular management types are an effective way to make existing efforts visible (Bayraktarov et al., 2020) but are needed on a much larger scale. In the current state, the literature on decision processes for conservation management seems to paint a very limited picture of conservation management decisions around the world.

4.5 | Reasons for limited uptake

Conservation science is not limited to realistic planning but also aims to progress methods and theoretical concepts or reports new data. Therefore, a certain amount of literature on decision processes, particularly in academic contexts, is expected to focus on the nuances of specific novel aspects of a complex decision instead of reporting in detail on the whole process. However, we also found a large fraction of applied examples with low numbers of critical decision elements. This indicates that insights from decision-science have not yet become standard in decisions that inform conservation practice, or at least are not reported in the published documents that describe practices. There is a range of potential scenarios in which the use of all elements may not be necessary or possible. For example, we could not assess if conservation scientists used key elements but did not adequately describe the details or simply failed to present them. One reason for not using some elements is the inherent trade-off between resources spent at planning, including decision-making, and resources spent on action (Buxton et al., 2020). In many cases, conservation actions are opportunistic (Meir et al., 2004; Pressey & Bottrill, 2008), and decisions have to be made quickly, or budget and expertise do not allow for a detailed decision-making phase. For example, the deliberation on trade-offs between multiple objectives can easily become complex and time-consuming. Involving stakeholders to scope out additional objectives and discuss trade-offs requires time, resources, and additional skills of facilitation and maneuvering group dynamics, which adds to the complexity of a more narrowly framed problem context. Scoping and running additional ensembles and sensitivity analyses is similarly time and resource consuming. Although these reasons are compelling arguments for the necessary balance between feasibility and rigor, we believe it is most important to acknowledge the importance of key elements during decision-making and to be transparent on the reasons when omitting them. That way, the conservation community would facilitate understanding and best practice, and make it easier to evaluate successes and failures.

4.6 | Representativeness of results

It could be questioned if the 466 examples that we identified in this review are representative of the comprehensive literature on academic and applied decisions on conservation management actions. There are likely many published examples of decision processes that do not include the phrase "decision-making" in the main text, and only a small fraction of existing gray literature is synthesized into peer-reviewed publications. However, the identification of 128 conservation practice examples in a sample drawn from a database of peer-reviewed literature was much higher than we expected when considering the often cited and controversially discussed "implementation gap" (Sunderland et al., 2009). Additionally, the use of key decision support elements was more strongly related to the use of specific frameworks than to the context of applied conservation practice versus academia. Hence, we believe our sample to be representative of the broad range of contexts, including genuine applications.

The number of identified publications that utilize MCDA is similar to a recent review (Adem Esmail &

Geneletti, 2018). In contrast to Esmail et al., we did not find a strong dominance of locations in Europe, with similar numbers of examples in the United States. This difference might stem from our focus on management actions for biodiversity conservation, which excluded a larger number of site-selection studies for industrial purposes. Another difference is the higher rate of sensitivity or uncertainty analysis, with 80% of examples in our review including some sort of sensitivity or uncertainty analysis, while Esmail et al. reported rates under 60%. A dominance of academic examples for SCP is supported by earlier assessments (Knight et al., 2008; Kullberg & Moilanen, 2014), but also contrasted by a recent survey that found similar numbers of examples, but where most were intended for implementation (Sinclair et al., 2018). Overall, we felt that the total numbers of papers and different frameworks can, compared to these other studies, be considered as a representative sample.

Classifying text is not a trivial task, as a different judgment on the same issues is common among experts (Kahneman et al., 2021). Even though we developed and tested instructions for choosing categories during the coding phase, making a judgment on the use of a specific element based on descriptive text is difficult. For example, one publication (Koehn & Todd, 2012) focused on the importance of trade-offs, and described it with theoretical examples, but did not use it for a final decision. A second paper (Chadés et al., 2015) mentioned trade-offs only briefly, but presented a figure that showed that they based their choice of action on information from a trade-off analysis in the form of a cost–benefit curve. To avoid difficult subjective judgments, such as coding the inclusion of trade-offs based on the judgment if it has been described in "enough" detail, we decided to code a trade-off only as present when it was clearly used to inform the final choice of management strategy. This is a clearer condition, as it did not need subjective judgment on how much description is enough and where to draw the line when trade-offs were described (sometimes in great detail) but were not used. We acknowledge that we were only able to classify what was described in the text. In many cases, key elements might have played a role in the decision but were not described in the publication and could therefore not be coded. Published documents about decisions that do not describe all key elements that were used are unfortunately not very useful to inform readers on how the decision was made and how rigorous the process was, despite the text's potential usefulness for other matters. Our results suggest that it is common practice among conservation scientists and practitioners to omit key decision elements frequently in their decision-making processes, or to at least not include them in descriptions of these processes. If this is true, the scientific literature is not a good place to look for fundamental guidance for decision-making processes but can only provide additional inspiration when it comes to novel approaches or specific details in the decision process.

4.7 | Conclusion

If conservation scientists and practitioners want their publications to improve and inform management strategies, decision processes should be based on insights from decision-science, and the use of key decision elements should be reported more transparently and comprehensively. The intent of our study is to encourage the conservation community to embrace the discussion and use of these five elements of robust decision-making, and to report transparently about factors that hinder their inclusion in decision-processes. Academic studies need to increase the focus on decision-making strategies and management types that are common in applied contexts. Some specific circumstances do not allow the inclusion of all elements due to lack of data, time constraints, or other means, but decision-makers need to be aware of the increased risks that they invite through a less rigorous decision-making process. While outcomes of conservation actions are most often uncertain due to the inherent complexity of natural systems and their inherent uncertainties, the process of decision-making can be used to judge the quality of the decisions being made (Hammond et al., 1998; Riley & Gregory, 2012). Such a process leads to the creation of feasible and realistic strategies for the implementation of management actions on the ground. Time and budgets are limiting existing efforts to protect our fast-disappearing natural heritage on this planet. Robust decision processes should be a high priority when people make choices about the course of action that is most promising to change the ongoing trend of loss of biodiversity. Finally, in order to understand and learn from the current state and trajectory of applied conservation management on a global level, there is a need to translate existing descriptions of conservation decisions from other languages into the English-speaking literature. We recommend that decision-makers seek detailed instructions beyond publications in the field of conservation to be able to employ rigorous practice during the decision-making process when planning for the conservation of biodiversity.

ACKNOWLEDGMENTS

We thank the John Hodgson Scholarship for making $6400 available to realize the experiment and the Research Training Program Scholarship Australia for enabling the research conducted for this manuscript. We would also like to thank Dr. Bonnie Wintle and Professor Fiona Fidler for their input into the overall process of rating categorical data, including discussion of the classification categories. Open access publishing facilitated by The University of Melbourne, as part of the Wiley - The University of Melbourne agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data and code are made available on figshare (https://doi.org/10.6084/m9.figshare.17205713.v1).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Beher, J., Treml, E., & Wintle, B. (2024). 10 years of decision-making for biodiversity conservation actions: A systematic literature review. *Conservation Science and Practice*, e13170. https://doi.org/10.1111/csp2.13170

PLOS One

RESEARCH ARTICLE

Group discussions improve reliability and validity of rated categories based on qualitative data from systematic review

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Citation: Beher J, Treml E, Wintle B (2025) Group discussions improve reliability and validity of rated categories based on qualitative data from systematic review. PLoS One 20(6): e0326166. https://doi.org/10.1371/journal.pone.0326166

Editor: Frank H. Koch, USDA Forest Service Southern Research Station, UNITED STATES OF AMERICA

Received: September 19, 2024

Accepted: May 26, 2025

Published: June 18, 2025

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pone.0326166

Abstract

The number of literature reviews in the fields of ecology and conservation has increased dramatically in recent years. Scientists conduct systematic literature reviews with the aim of drawing conclusions based on the content of a representative sample of publications. This requires subjective judgments on qualitative content, including interpretations and deductions. However, subjective judgments can differ substantially even between highly trained experts that are faced with the same evidence. Because classification of content into codes by one individual rater is prone to subjectivity and error, general guidelines recommend checking the produced data for consistency and reliability. Metrics on agreement between multiple people exist to assess the rate of agreement (consistency). These metrics do not account for mistakes or allow for their correction, while group discussions about codes that have been derived from classification of qualitative data have shown to improve reliability and accuracy. Here, we describe a pragmatic approach to reliability testing that gives insights into the error rate of multiple raters. Five independent raters rated and discussed categories for 23 variables within 21 peer-reviewed publications on conservation management plans. Mistakes, including overlooking information in the text, were the most common source of disagreement, followed by differences in interpretation and ambiguity around categories. Discussions could resolve most differences in ratings. We recommend our approach as a significant improvement on current review and synthesis approaches that lack assessment of misclassification.

Introduction

The number of reviews in the fields of ecology and conservation has increased dramatically in recent years. Reviews take science to a meta-level that is needed

Data availability statement: Data and code is uploaded in figshare: https://doi.org/10.6084/m9.figshare.26889553.v1

Funding: John Hodgsons Scholarship was awarded from University of Melbourne ($6400 AUD) to realize the interrater reliability experiment and the Research Training Program Scholarship Australia was in general awarded to conduct the work within a PhD thesis. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

to transcend the focus and unique circumstances of individual studies, enabling generality. When researchers conduct a review, they search the published literature with a specific question in mind and often use a rubric or filter to find publications that contain relevant content for the question they want to answer. General guidelines for conducting reviews and other meta-analyses aim to facilitate unbiased and repeatable results and include recommendations for asking a second and sometimes subsequent researcher(s) to go through the same process of selecting or interpreting texts using a subsample of included publications and compare the judgments that were being made [1].

A standard part of the methodology when conducting a review is to extract data from the existing literature. While systematic and other structured reviews often classify content into categories, which is most often done by judging content based on a coding scheme, narrative reviews make judgments on content in a rather informal way, possibly drawing more on subjective intuition or interpretation without a standardized protocol. Unfortunately, making judgments about content is not a trivial task, and misclassification can easily occur [2,3]. If error or bias are not detected during peer review, the impact on the field of science could be substantial and long lasting, as even retracted studies continue to collect citations [4,5]. The citation report from Reuters Web of Science for systematic or literature reviews in the field of ecology and conservation shows a steady increase of reviews with an average citation rate of 76 and an h-index of 326 as of June 2021, restricted to reviews and journals with focus on biology and ecology and based on the search terms "systematic review" OR "literature review" AND "ecology" OR "conservation". As reviews are rarely replicated and are, on average, more than twice as often cited as other publications, it is important to ensure the reliability and validity of the coding categories used. Unfortunately, this is not common practice: for example, only three in the 26 most cited and none of the 24 most recent publications that we found in our Web of Science search reported completion of any reliability checks or even stated the general importance of doing so.

Content analysis differentiates between three types of content that differ in the amount of interpretation a reader must do. These types are manifest (coding based on pure detection), latent pattern (coding based on detection plus additional cues) and projective content (coding that requires deduction) [6]. Classification that goes beyond manifest content brings subjective judgments into the process and, hence, uncertainty. Processes that include subjective judgment in addition to pure detection require validation and need to be reliable because of the risk of errors being made during interpretation of different cues in the text. When additional cognitive tasks beyond detection of words are involved in a classification task, for example, interpreting the context in which a word is used and making a judgment based on this interpretation if a specific condition is met, additional possible sources of mistakes or misinterpretation are introduced. General recommendations for reliability tests suggest the use of multiple raters in the process of coding in order to produce reliable data [7–9]. Information on agreement is commonly used during a testing phase to identify problems like unclear categories in the coding scheme and, based on parallel coding of a smaller subset, as an indicator for the reliability of the whole data set.

Multiple metrics [10,11] have been developed to assess rate of agreement between raters as a proxy for reliability. Although reliability is a prerequisite for validity, reliability metrics cannot inform about the validity of tested data [10]. There is a difference between how often people produce the same code (reliability) and how often raters give the best possible answer compared to the actual content of the source (validity). Therefore, agreement that is based on misclassification can increase reliability but at the same time decrease validity and, in the worst case, will make people trust data that does not reflect the actual content of the coded texts.

Unfortunately, testing for validity is difficult. While an objective standard exists for manifest content, against which any rating can be compared (for example, presence/absence like counting the frequency of a word, or testing for a substance in a blood sample), an objective standard in the form of an uncontroversial agreement on interpretation does not exist for latent pattern or projective content and needs to be constructed (for example, the use of a word in a specific context, or the contribution of a detected substance to a health problem). The construction of any standard for latent pattern and projective content requires a certain amount of human judgment, which is inherently subjective, and the resulting standard can, therefore, never be fully objective. The practice to designate the main rater as a point of reference is common [12] but has been questioned because assumed expertise has often been shown to be unjustified when tested [13]. Therefore, a thorough, rigorous process for accounting for subjectivity and error is needed.

The situation that an objectively perceived correct interpretation is unknown and all that can be used is a well-informed subjective judgment is very similar to the context of expert judgment [14,15] and expert elicitation [16]. Therefore, measures that are used to improve data quality in these areas of research, particularly the use of group discussions, seem to be promising tools for testing the validity of coded data in content analysis.

The positive impact of group discussion on agreement between independent raters has been described in the field of medicine [17]. More recent research on expert judgment and elicitation has shown that the reliability and accuracy of judgments usually benefit from an exchange of thoughts and assumptions of individual raters in a group setting [14,18–22]. Even though many of these examples focus on estimation of quantitative data in natural sciences and risk analysis, similar recommendations can also be found in the social sciences regarding qualitative data [12], specifically the importance of discussion during rating exercises when there is *"great sensitivity not only to obvious meanings but also more subtle meanings, and where coders have different levels of knowledge in this regard"* [7]. In the context of business decisions, discussions have been identified as more important than rigorous process [23]. In addition to biases, which represent directional errors, errors that appear as unwanted variability in judgment of people who must choose between options have been termed 'noise' and are often surprisingly high across many professions despite extensive education and training [24]. Here, we consider *mistakes* as errors that create noise and use the term *error rate* when referring to the frequency of these mistakes.

Reading scientific publications is intellectually demanding because their comprehension requires knowledge of the used terminology and concepts in the context of the relevant discipline. Knowledge held by individuals will be similar across scientists from a particular field but will differ in breadth, depth, nuances, and school of thought. In addition to the differences in expertise and the ever-present chance of making simple mistakes, scientists are subject to different kinds of biases when making judgments, both on their own and when in groups. Protocols have been developed that enable people to make judgments with as little bias as possible [19]. To capture the widest possible range of knowledge and subjective judgment, it is important to give individuals the chance to make initial judgments on content on their own. Independent judgments protect from biases introduced through human interaction, such as groupthink and dominance. However, to mitigate biases that matter in individual thought processes, such as availability bias or confirmation bias, feedback and discussion of assumptions and evidence are required.

By facilitating a group discussion after each rater has completed a coding task individually, individual and group relevant biases can be addressed, while unintended disagreement can be corrected when the raters themselves believe they made a mistake and only true disagreement based on convictions is retained. Where misclassification has occurred due to simple mistakes, it is likely that raters, if given the chance to correct their mistakes, will be able to resolve some disagreements, while new disagreements might be discovered. At the same time, insights into the error rate of individual raters can be gained by quantifying how often raters change their coding decisions, for each category within all rated texts, after discussion. The resulting data would likely be more reliable and more accurate than without such an assessment of evidence for produced codes.

Building on insights from expert judgment as well as social sciences, we describe a case study that trials a combined assessment of reliability and validity of coded data in three steps: By linking conventional parallel coding (step 1) to a subsequent reflection by the raters on their ratings (step 2), followed by a group discussion (step 3), we are able to measure the rate of change due to errors, or changed beliefs. The analysis of these rates of change in agreement produces metrics that go beyond raw initial agreement rates. These metrics include the percent agreement on categories before and after group discussions and error rates for individual raters and variables. The results allow insights into both reliability and validity of the produced codes.

We demonstrate the application of this protocol using 25 published papers that report on conservation decision processes, coded for a structured literature review on conservation decisions [25]. We demonstrate rater learning by comparing error rates and rates of persistent disagreement using five raters who engaged in individual reading/coding followed by group discussions over a 12-month period.

Methods

To assess the impact of group discussion on the quality of categorical classification of text, we drew on a published dataset of decision-making processes for conservation management [25]. The study sampled the peer-reviewed literature with several search strings to find published texts on conservation management decisions that were derived through a prioritization process. The first author coded all texts for several variables and respective categories, requiring some degree of interpretation, and provided quantitative summaries of these categories as results. The group discussions were used as a means to validate the quality of the codes, with the author (in the following referred to as "main rater") facilitating the experiment and comparing their own ratings and arguments with a group after independent parallel coding.

Workflow

25 publications were randomly selected from a pool of 466 publications [25], while being stratified across subgroups based on citation rate to include publications with highly cited and rarely cited publications in the experiment. Five raters coded in parallel categories for 23 variables (Table 1) using the provided coding scheme (Supplementary material S1A and S1B Table) and participated afterwards in a group discussion with the option to revise their codes following conversation. All raters were students of environmental sciences with a focus on conservation. Three raters were in the mid or end phase of their Bachelor's degree, and one rater was in the final stages of his Master's degree. Available funds were used as a primary stopping rule and all raters were paid for individual coding and discussions with a standard hourly rate until the money was used up. The moderate sample size of 25 papers is justified as a reasonable sample in light of budget and time constraints [26].

To provide some introduction and training, five publications were used in a pilot study to familiarize raters with the task and to test the clarity of categories within the coding scheme, which resulted in adjustments to the coding scheme where raters reported difficulties (Table S2).

The rest of the experiment consisted of parallel coding of categories for 23 variables for each of 21 publications (one publication overlapped with the pilot) by the same four additional raters. The work was split up into several sessions with a duration of a few hours each to allow raters to remember the details of the rated publications for the group discussion, before rating the next set of publications. Six rounds of coding were needed to work through all publications, each consisting of individual rating of text followed by a group discussion. The first round included one publication, all other rounds

Table 1. The 23 variables and the number of possible category codes within them. Combinations of options were coded by entering multiple codes separated by a comma.

	Variable	Label	Type	Possible categories (in addition to NA)
1	Context of decision	implementation	nominal	2 options
2	Framework used	framework	nominal	6 options
3	Country	country	nominal	186 options
4	Continent	continent	nominal	5 options
5	Spatial scale	spatial scale	ordinal	6 options
6	Type of management	management	nominal	5 options
7	Threat type	threat	nominal	11 options
8	Threat presence	threat present	nominal	Checkbox (presence/absence)
9	Species	species system	nominal	14 options
10	Realm	realm	nominal	3 options
11	Type socio-economic considerations	socioeconomic	nominal	7 options
12	Inclusion of socio-economic considerations	Socioeconomic present	nominal	Checkbox (presence/absence)
13,14,15,16	Type environmental, social, economic and other objectives	environmental obj social obj economic obj other obj	nominal	Each 2 options
17	Count objectives	count objectives	numerical	4 options
18	Count of options for decision	count actions	numerical	4 options
19	Tradeoff included	tradeoff	nominal	Checkbox (presence/absence)
20	Sensitivity analysis presence	sensitivity present	nominal	Checkbox (presence/absence)
21	Sensitivity analysis type	sensitivity	nominal	9 options
22	Cost included	cost	nominal	4 options
23	Feasibility included	feasibility	nominal	2 options

https://doi.org/10.1371/journal.pone.0326166.t001

included 3–5 publications. Before the group discussion, the individual ratings were compared, and a list of disagreements was sent out to raters to assist with their preparation for the discussion, with a first option to correct for obvious misclassification. This measure was introduced because the first discussion took more than three hours for one publication, and this change allowed us to successfully reduce the discussion time to one hour per publication, as revisiting the text and confirming evidence for codes was the largest time sink.

The discussions focused on disagreements on any classification. For each category with different classifications from different raters (for example, classification "invasive species" and "pollution" in variable "threat"), each rater shared their evidence from the text on which their judgment was based, as well as any related assumptions. The raters shared their codes for each category in each paper by reading out aloud to create an overview of the range of entries, confirm agreement and discuss existing disagreements. Raters had a second option to adjust their codes during the discussion. The disagreements that remained after code revision opportunities were regarded as true disagreements.

Group effects like dominance and group-think were counteracted by having a first round of individual rating to collect the full range of individual codes and reminding raters during the ensuing group discussion that agreement was not a necessary outcome. The distinction between unintentional misclassification and genuine disagreements over interpretation was repeatedly explained, and counterarguments and true disagreement were encouraged. The discussion was facilitated to make sure everyone was heard, and three different types of questions were asked:

1) Can you provide evidence from the text to justify your code?

2) Do arguments for different interpretations of text exist?

   a. Is the coding consistent with instructions?

   b. Is the coding consistent with other coding entries (e.g., ticking the box for the presence of socio-economic objectives might mismatch with empty related fields)?

3) Have we already discussed similar codes, and is our argumentation consistent?

All data were edited during discussions in Microsoft Excel. One csv file with all codes before each discussion session and one csv file with adjusted codes after the session was created for processing and analysis in R [27], specifically packages *tidyverse* [28], *reshape* [29], *stringr* [30] and *stringi* [31]. Data and code are publicly available on figshare [https://doi.org/10.6084/m9.figshare.26889553.v1].

Studies in which the outcome is a quantitative measure often summarize agreement with Fleiss' *kappa* (in the following referred to as "kappa"), which is a percent agreement measure which accounts for agreement by random chance, for example, when raters have to decide between two categories that are placed next to each other on a quantitative scale. However, our data do not contain many numerical or ordinal variables, hence random agreement was not likely to occur. In addition, metrics like Cohen's kappa, Fleiss' kappa, Krippendorff's alpha or Scott's pi all make the assumption that coding decisions by raters are made independently [10,11]. Our use of a group discussion in the process would violate this assumption. Because of this, and because our data are predominantly nominal and similar to student assessments [32], we decided to tailor our analysis to the data and use percent agreement to calculate metrics of reliability and validity.

We produced two different types of information: first, percent agreement as a measure for reliability of the coding as a procedure that is subject to individual judgment, and second, the frequency with which raters changed their mind about their initial entries as a measure of how trustworthy the code from individual raters was compared to the other raters, and how trustworthy the codes for individual variables were compared to the other variables. This method aims at reducing disagreement based on error, while retaining true disagreements based on interpretation of the categories or the text itself.

Following McHugh (2012), the average percent agreement between the main rater and other raters was calculated as a measure of reliability, and a proxy for the consistency of codes across raters [33]. The average agreement was calculated by first calculating percent agreement for each variable across all coded texts before and after group discussion in pairs between the main rater and each of the other raters, which resulted in four values of percent agreement. The average of these four values was used as a measure of misclassifications and true disagreement on latent content from qualitative text.

The rate of change in coding after discussion was used as a measure of validity, regarding how often the raters thought their own codes to be accurate after having been exposed to a range of interpretations. A measure of confidence regarding collected data is not new, as, for example, Hanea (2017) and Hemming (2018) both incorporated a measure of confidence of individuals who participate in producing estimated data values [14,20]. They asked people to estimate four values, data best estimate, bounds around the estimate, and a value for a self-assessed level of confidence. Their measure of confidence gives information about the intrinsic belief of the rater in their own accuracy. In contrast to their intrinsic measure of confidence, we created a more objective measure of confidence that indicates if a rater's data is robust when tested against other raters, based on how often individual raters change their rating. Our measure of confidence gives information on the ability of each rater to produce codes that are unlikely to be changed when ratings and the underlying evidence in the rated text are scrutinized by others. We recorded the frequency of changed ratings after discussion for all raters across all variables. The resulting set of metrics were (see calculations in S3):

a. The main rater's average error rate and standard deviation can be used as a measure for the likely validity of the full data set (which is coded by the main rater only)

b. Error rates and standard deviation of individual raters are an indication of the importance of multiple raters by providing insight into between-rater variation in error rates and standard deviations. If most additional raters have a significantly lower error rate compared to the main rater, it can serve as an important warning sign regarding the quality of the data set that has been produced by the main rater.

c. Error rates for the categories within the 23 individual variables, averaged across all raters, can guide interpretation and adjustments of data for further use, such as collapsing categories when error rates are high.

We accounted for two potential sources of uncertainty: (i) frequency of categories and (ii) numbers of additional raters. The relative frequency of variables (*prevalence*) can influence the rate of agreement. The comparison of agreement rates between variables that were frequently encountered, and variables that were rarely encountered during the rating can be difficult [34]. We, therefore, compared the metrics for two-factorial subsets of the data for categories for variables that were coded in more than 50% of the produced codes across all raters (frequent subset) and less than 20% of the produced codes (rare subset). The precision of averaged estimates depends on sample size and number of raters and has been shown to improve with increasing numbers of additional raters [8,35]. We tested for the effect of number of coders by calculating percent agreement for all possible main rater/additional rater pairs and averaged the values for all permutations of one, two, three or four of the additional raters. The acceptable level of agreement depends on the purpose. For important decisions a minimum of 90% is suggested, with 80% tolerable in many other settings [36,37].

Recommended thresholds for different agreement rates to pass a reliability test are given in the literature, for example, 60% for kappa [1] or 80% for Krippendorff's alpha [38]. However, generally accepted methods to derive context-relevant acceptable thresholds that warrant drawing conclusions from the data have not been established, and the choice of a threshold is always somewhat arbitrary [9,39]. Here, we consider a percent agreement of > 80% as acceptable.

Results

We found that group discussion led to a clear increase in percent agreement for all variables (Fig 1) and, by implication, a higher reliability of the coded findings. This pattern was particularly strong for the variables with a high frequency of multiple, combined entries, like multiple threats, species, socio-economic objectives, type of management or type of sensitivity analysis. More than half of the 23 variables showed an initial percent agreement (Step 1) of less than 80%. All variables except *for type of sensitivity* and *species*/*system* passed this threshold after the group discussion (Step 2), with 18 out of 23 variables above 90% agreement and 6 variables 100%. This means almost all disagreement was resolved through discussion (Fig 1). This was not only the case on average but a repeated pattern through all rounds of coding (Fig S4). The improved percent agreement after discussion leads to different conclusions about the reliability of individual variables and categories than the use of kappa or alpha (Table in S5), with 8 categories that would fail the reliability test based on kappa, overlooking that most reasons for disagreement were based on unintended mistakes, and an agreement rate of over 90% after these were detected during discussion.

All raters, including the main rater, changed some codes for at least some categories after the discussions, which allowed the calculation of an error rate for raters and variables (Fig 2). These error rates were compared and used as a measure of validity of answers in the full data set. Most variables with a higher average error rate also had a larger standard deviation, indicating that not all raters made mistakes, while the variable "type of sensitivity analysis" showed a high error rate and small standard deviation, indicating that all raters made many mistakes. The main author kept, on average, almost 90% of their codes unchanged, with a lower average error rate and smaller standard deviation than the additional raters, indicating good quality of coding.

Our sensitivity analysis did not find a clear effect of the frequency of different variables (Fig 2). We found a clear effect of the number of additional coders on the rate of agreement when calculating percent agreement across all possible combinations of raters, while calculating kappa across the same combinations of raters did not show any impact of the

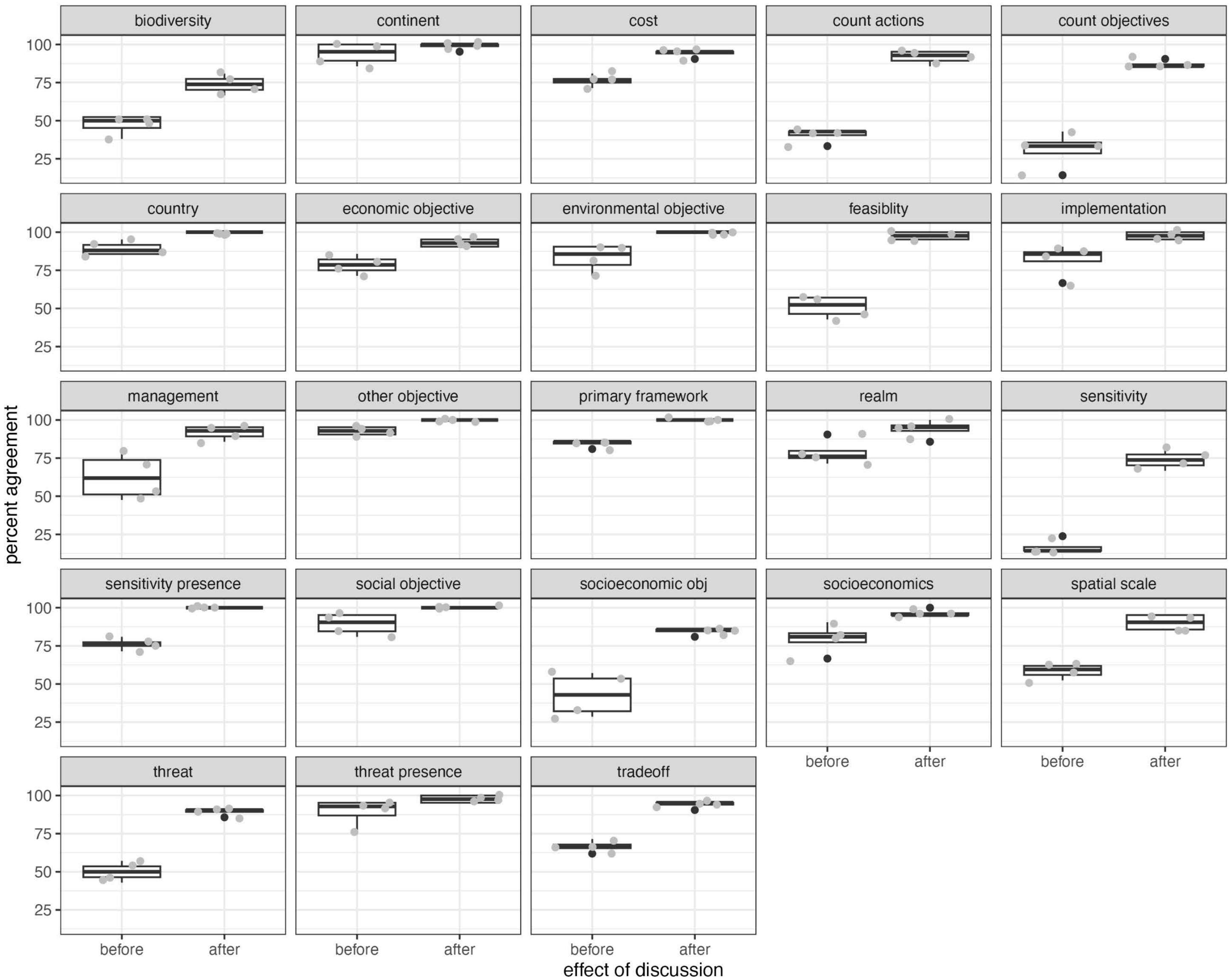

Fig 1. Percent agreement between the average group of four raters and the main rater for 23 variables before and after group discussions for 21 publications after the pilot. The effect of group discussion to remove misclassification and retain true disagreements is clear for all variables. Black dots show outliers, while grey dots display all data via jittering. Note that jittering allows to see all points by pushing them apart, in some cases beyond the accurately located outliers in black.

https://doi.org/10.1371/journal.pone.0326166.g001

size of the groups except for increased variance, reflecting the larger number of possible rater combinations to compare to each other (Fig 3 - 5). We also did not find any indication of an improvement in the error rate or rate of agreement over the period of the study.

Most variables would fail the inter-rater-reliability test with the use of kappa, with many values below the recommended threshold of 0.6 (Fig 3), reflecting the low percent agreement rates before discussion (Fig 4). Identification of unintended mistakes through group discussion led to overall higher agreement rates, in clear contrast to results with kappa (Fig 5).

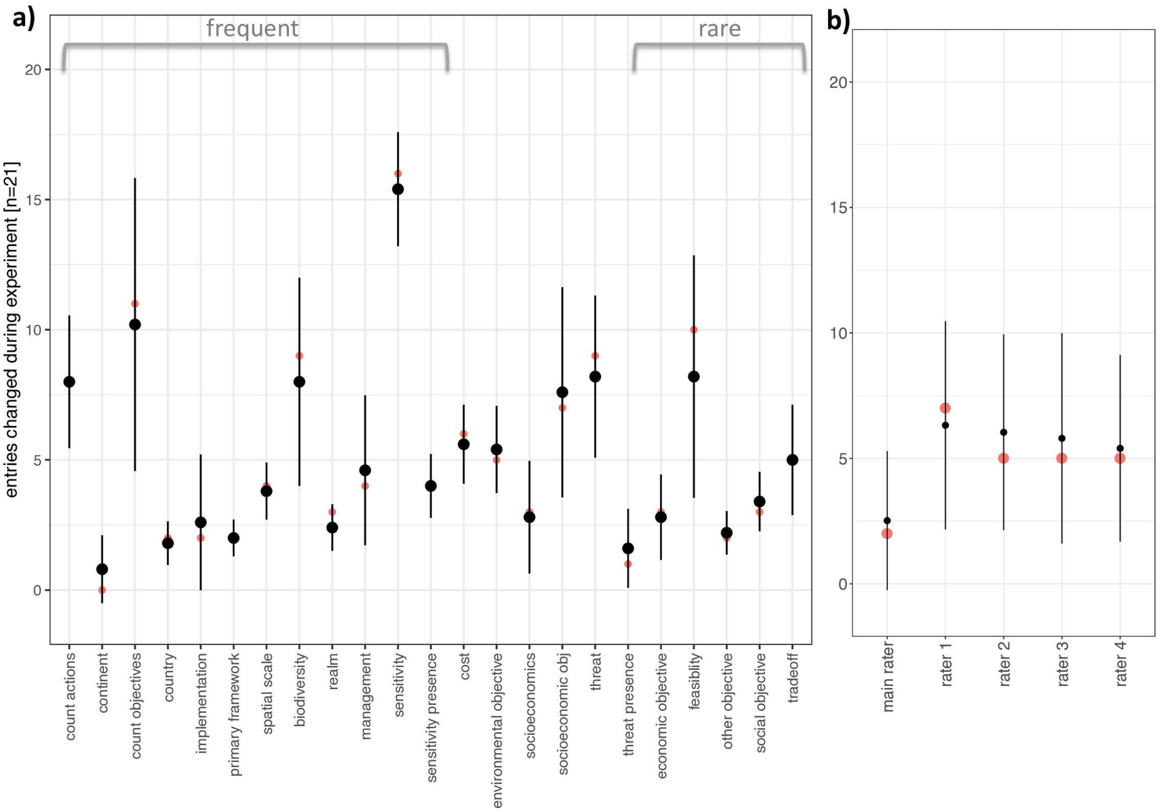

Fig 2. Average and standard deviation of the frequency of unchanged ratings for each variable across all five raters (a) and each rater across all 21 variables (b)**.** Medians are shown in red. Variables that were present in more than 50% of codes were considered frequent, and variables present in less than 20% of codes were considered rare.

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Discussion

Humans who make judgments on content make subjective interpretations, mistakes, and have biases, as all these are inherent traits of human thought processes. Our experiment shows that this subjectivity plays a large role, as the overall agreement between raters was low before discussions (Fig 1). However, we also found that agreement dramatically increased following conversation, with an average increase in agreement across all questions of 43% (from 45% to 88% agreement) following discussion. In over 50% of cases, full agreement was achieved following discussion. That is because disagreements arising from mistakes or misunderstandings of text were corrected when raters were given the chance to discuss their judgments and underlying reasoning and evidence with others. Discussion resulted in reduced misclassifications but retention of true disagreements. Our method of pilot assessment and calibration through discussion provides an easy and intuitive way to gain insights into the reliability and validity of literature assessments by reducing unintended variability [24].

What does this tell us about the general process of doing a narrative, structured or systematic literature review? Although guidelines acknowledge the importance of testing reliability [1,9], they do not go into detail about different testing options, and do not provide guidance on how to stem the substantial additional workload and investment that is usually needed to recruit multiple raters. Strategies of rigorous process, testing categories and training raters are suggested to improve the chance of objectively agreeable judgments. However, our results suggest that finding agreement through

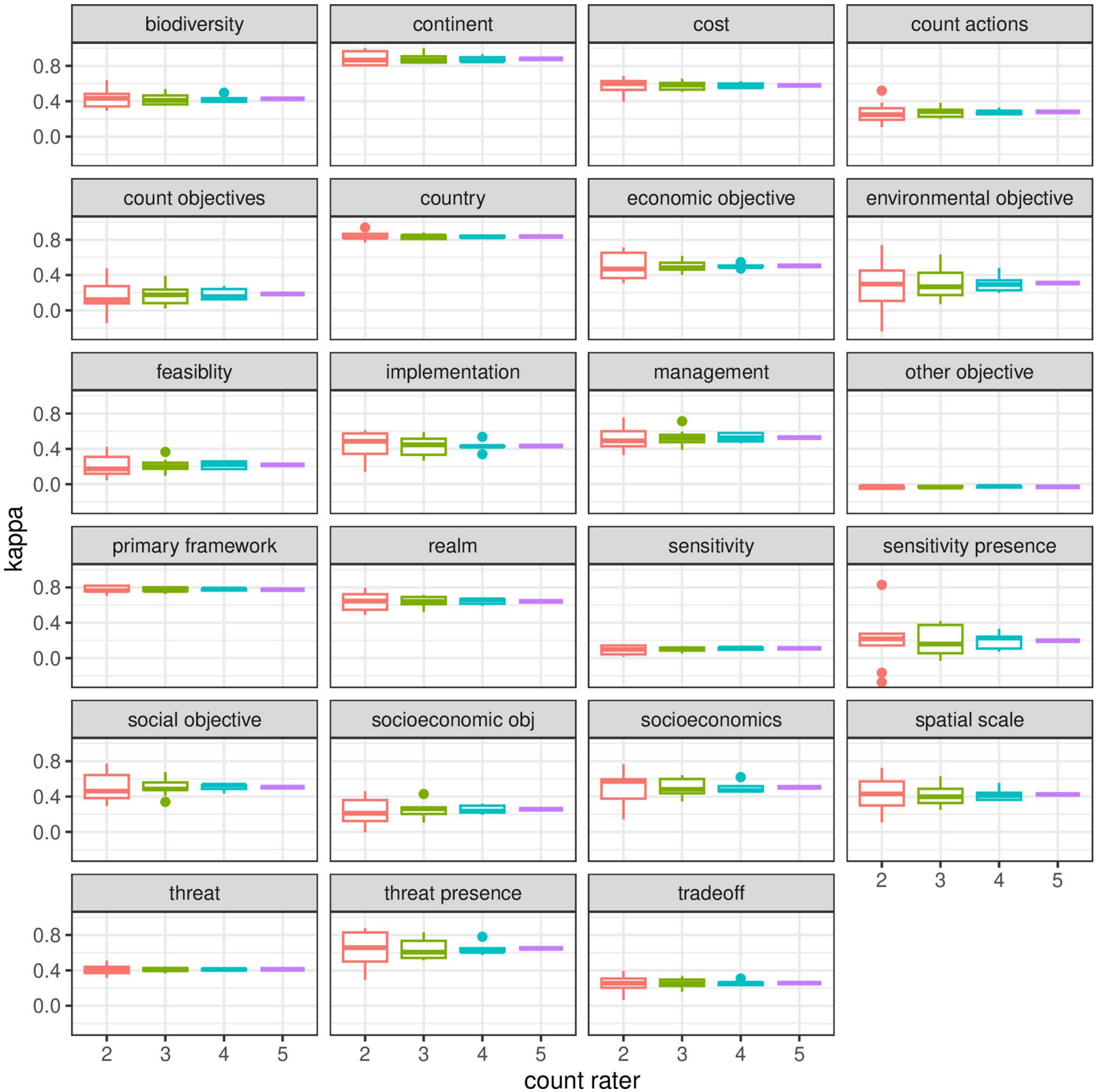

Fig 3. The calculation of kappa for all possible groups of 2,3,4 or 5 raters did not reveal any impact of group size on pre-discussion agreement.

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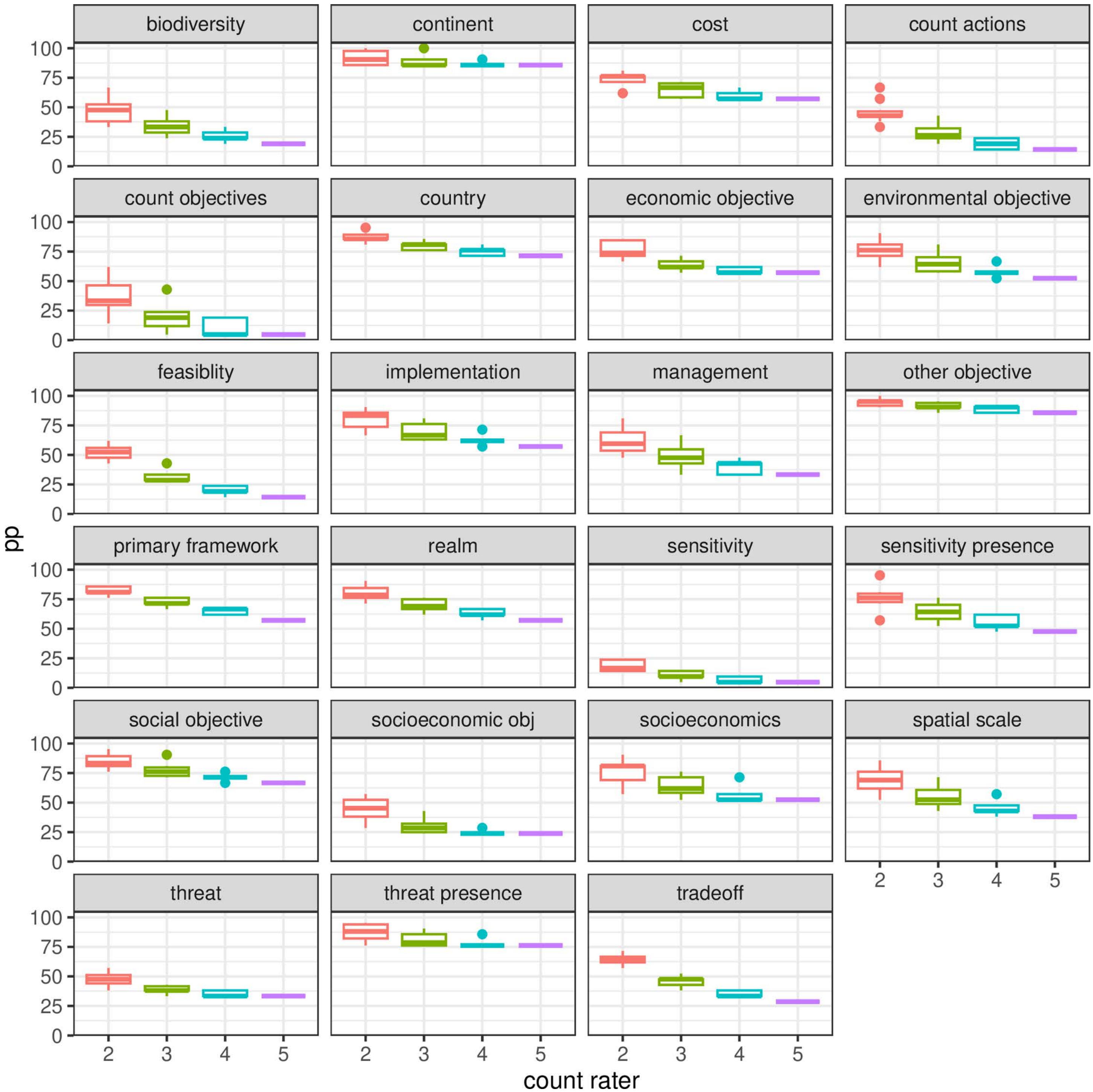

Fig 4. The calculation of percent agreement for all possible groups of 2,3,4 or 5 raters showed that percent agreement was lower for more raters, which is different to findings for coding of quantitative estimates, where the main across all raters is more likely to converge to the accurate value (Marcoci et al. 2019).

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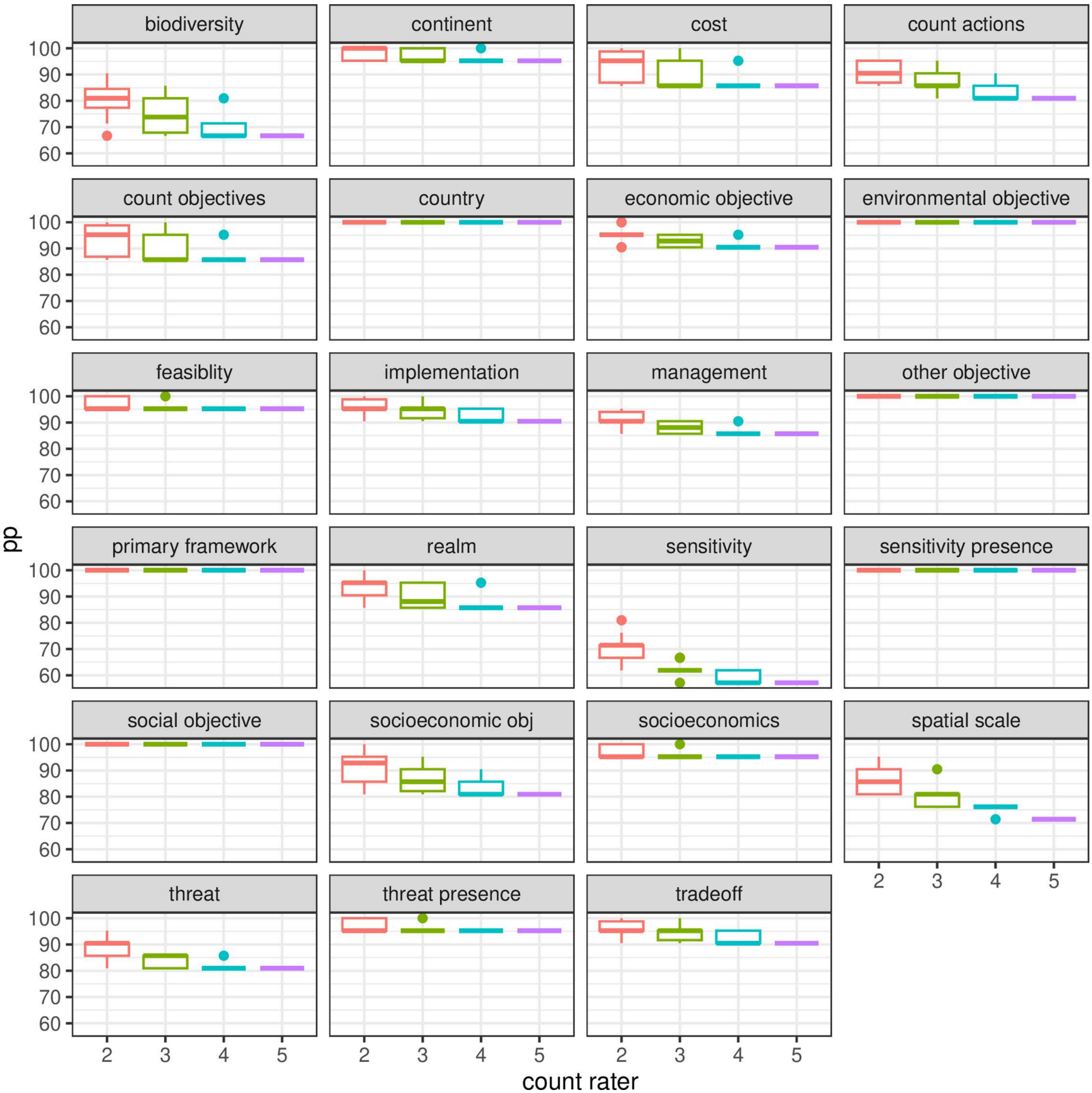

Fig 5. Percent agreement across all combinations of raters still shows a negative trend for larger groups after the discussion, albeit with overall elevated agreement rates for all variables.

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conversation is very effective in solving problems, including spelling mistakes and oversights, which are unlikely to be overcome with the standard strategies.

Our experiment demonstrates that the opportunity to discuss judgments not only increases agreement between raters but also gives insights into error rates of individuals, which can inform about rater quality. Science relies on narrative, structured and systematic reviews to build broader understanding of patterns and concepts. Scientists who undertake a review need to be aware of the potential large error rate they might have when judging texts, especially when judgment and interpretation of context in addition to the detection of plain presence of specific words is required. Being aware that review processes are inherently subjective processes should encourage scientists to calibrate their own reliability by exposing themselves and their rubrics to the critical feedback of others during the review process. We all strive for accurate insights when doing reviews, but without the help of others, it is not possible to find out if we made mistakes in our judgments.

A reliability-checking process which relies on calculating kappa to see how reliable coding is between raters *but does not engage in discussions to interrogate why raters might have disagreed* will not be able to distinguish unintended mistakes from actual, earnest differences in interpretation. Mistakes create unwanted variability on the individual level, obfuscating the detection of legitimate differences in interpretation. Identifying these mistakes makes it possible to detect and address problems, including ambiguities in the coding scheme or difficulty of the rated content.

We therefore believe our method to be better equipped to assess the overall quality of text-derived qualitative literature analysis than metrics that evaluate initial agreement, such as kappa or alpha, which account for chance [10]. For example, 8 variables that would fail the interrater test by using kappa show over 90% percent agreement rate after discussion, indicating the high rate of unintended mistakes (Table S5). This is particularly the case when ratings are made beyond manifest content (for example, coding based on pure detection of specific words) and are subsequently used for quantitative summaries and synthesis of qualitative information. As this is the case for many literature reviews, and these syntheses are highly cited and influential, the additional information that provides a quality-check is worth obtaining.

There were three different types of causes for disagreement: disagreement by mistake, disagreement due to ambiguity in categories, and disagreement due to ambiguity in the content that was to be classified. We discuss each of these and the implications for reliability and validity in the following.

Mistakes were the most common reason for disagreements, rather than fundamental disagreements of interpretation Agreement rates increased drastically after the opportunity to correct mistakes after exchange (Fig 3 and 5). The most frequent underlying causes tended to be forgetting to check tickboxes, entering the wrong code number, and overlooking text. The benefit of discussions to flag mistakes was very clear but time-consuming. We were able to improve time efficiency considerably by building some interdependencies and overlap into the coding scheme. Doing so allowed us to check for inconsistencies and flag errors in raters' answers prior to discussions. For example, a question that asked whether socio-economic objectives were present was somewhat redundant, given that another question asked raters to identify the "*type of socio-economic objective*" present in the study. But the combination made it often possible to detect missing entries, and raters could be given the chance to fill in their gaps and join the discussion with complete codes.

Mistakes were often caused by difficulties in sustaining attention during reading. Coding for variables that required picking up multiple cues in different passages of the text created significant challenges for raters and led to disagreement between raters. For example, there was high agreement between raters about whether sensitivity analysis had occurred in the analyzed texts. However, there was low agreement about what the specific types of sensitivity analysis were. In most cases, multiple descriptions of how uncertainties were explored were mentioned throughout manuscripts, and there were rarely dedicated concise sections in the analyzed texts. Discussions revealed that the most common cause of rater disagreements for this variable seemed to arise from raters simply overlooking cues within the text, and not from lack of clarity in the writing. This could have been caused by a lack of understanding on the part of the raters about the subject matter in the texts, such that they could not discern correct answers from the available cues, or plain mistake by skimming or not focusing enough while reading.

A second cause of disagreement was an inherent ambiguity of categories

This was the case when coding categories may not have been clear or specific enough such that an unambiguously correct rating exists. Despite inbuilt mitigation via testing codes in a pilot and collapsing problematic categories, some residual ambiguity usually remains. An unfortunate characteristic of classification schemes that are founded on linguistic terminology is an inherent "fuzziness", which results in a lack of clear demarcation between different categories [40], inviting ambiguity. Semantic ambiguity in the available classification options presented to raters can introduce uncertainty and errors in answers they provide. For example, "mangroves" were classified as an individual species, trees, or a type of ecosystem by different raters. In another study, "native woodlands" were classified as forest or ecosystem by different raters, and there were different opinions on whether "unspecified locations in Victoria" were best classified as local or regional spatial scale, as both interpretations seemed plausible [41]. Although the discussion proved helpful in explaining the underlying cause of disagreement in the case of ambiguous categories, it did not help to resolve disagreement in all cases. Identifying for which variables this is an issue can help to refine the rating scheme and interpret the results.

Our pilot phase of the inter-rater-reliability testing had the objective of mitigating existing ambiguity as far as possible. We expected that we would be able to minimize the issue but not remove ambiguity completely, due to the inherent fuzziness of linguistic categories. Our results, therefore, confirm that even though ambiguity in coding schemes can rarely be removed completely, a pilot phase that aims to detect issues can minimize problematic codes.

Some texts were difficult to rate due to under-specificity in the text itself, requiring interpretation of content

Our findings support evidence that different readers package qualitative content in different ways when tasked with classification, despite overall agreement on broader themes [42].

Some interpretation was easier when raters had advanced knowledge of mathematics, ecology or decision theory, but some cases relied on purely subjective interpretation. For example, one text described several distinct species and taxa, such as waterbirds, in the introduction, but it remained unclear if these species were considered in the case study or just used as a reference for similar studies [43]. The discussion among raters could not clarify if the case study included data on waterbirds or only broader ecotypes because the underlying text was not specific enough, and no one could bring forward clear evidence for one case or the other. In a similar example, disagreement remained over whether "non-target species" in a plan for wild pig control were best classified as fauna or not because, although an example with other animal species was given, it was possible to imagine that some of the control activities would have an impact on vegetation [44].

Discussion and identification of frequent mistakes enabled the identification of problematic categories. In our study, seven of the 23 variables were coded with a high error rate, a low initial agreement rate and a higher standard deviation than other variables (Fig 2). Most of these seven variables (species, count of action, count objectives, type of threat, presence of feasibility, type of sensitivity analysis, and type of socio-economic objective) were more difficult for some raters than for others, although a general underlying cause for the divergence in rating is hard to determine. The exception is the variable "type of sensitivity", which can be identified as the only variable that was difficult for all raters, indicated by the high change of mind and low standard deviation. Collapsing categories can sometimes be the only solution to accurately code such a problematic variable. For example, it was often the case that raters had only detected a subset of the evidence in the texts regarding the variable *type of sensitivity analysis* and realized, once made aware of relevant descriptions in the text, that they had not paid enough attention and needed to add missing categories to their ratings, which led to high agreement after discussion. Another example was the broader agreement that uncertainty had been explored in one of the texts [45], but raters could not settle on one classification for the relevant parts in the text as different interpretations seemed plausible to choose the category of different values of parameters, different models, scenarios for different actions, differences of given scores, or a combination of these methods. The reduction to a presence/absence code when disagreement affects only nuances within a specific variable can serve as a more cautious and reliable replacement, albeit incurring a loss of information.

The main benefit of comparing different raters' error rates was to be able to make a judgment on the coding quality of the main rater

The main rater coded a much larger number of texts that could not all be included in a parallel coding stream due to time and cost constraints. But the comparison of error rates gave confidence in the untested codes because, on average, all additional raters had a similar error rate and changed their codes more often than the main author. In the hypothetical case that the main rater has a higher error rate, this information could flag concerns about the quality of the codes. In the case that there is no main rater and different raters code similar fractions of the sampled texts with some overlap, our method can identify raters that perform worse or better than others. This helps to make a judgment on the reliability and quality of the produced codes. If variables that have high error rates in all combinations of raters are detected, categories can be collapsed or dismissed. See S2 for examples of collapsed categories in our study that were identified during the pilot phase.

High heterogeneity of qualitative content in papers, as was the case in our study, makes it difficult to create the opportunity for training and learning

Training and learning ahead of rating have been important and well-proven mechanisms to increase accuracy of ratings for quantitative estimations [46]. The rationale that training can prepare sufficiently for rating procedures, and a time- and budget-intensive discussion after rating is therefore not necessary, might be posed as an objection to our proposed method. In the context of quantitative estimates, learning occurs more readily when quantities are repeatedly estimated in a consistent problem context, such as assessments of symptoms of a particular condition in health or assessments based on quantitative ecological or economic data [46,47]. In these settings, multiple rounds of feedback on estimated quantities enable raters to calibrate themselves through learning.

However, there are important differences between quantitative and qualitative codes, especially when content that needs to be rated is very heterogeneous.

While the repeated activity of estimating quantities seems a straightforward method to hone a specific skill, the required concentration to read long texts and pay careful attention to multiple qualitative categories and variables is a very different challenge. Our results have shown that most disagreement stems from a lack of focus and careless mistakes but very rarely from a misunderstanding of key concepts or a lack of knowledge that could be bolstered through training. A decreasing error rate over time would indicate that raters improve in accuracy by doing the same task repeatedly over time. While evidence has been collected to back up training as a tool in quantitative estimates [18,46], we could not detect such a decrease in error rates and, therefore, cannot confirm that raters improved their coding of nominal variables beyond manifest content by coding the same categories repeatedly over time (Fig S4). We also did not find that agreement was impacted by the frequency with which a variable was encountered. We interpret this as further evidence that training exercises with very heterogeneous data might be suboptimal compared to group discussions.

The lack of clear demarcation between classifications might also play a role in explaining why we could not detect any evidence of learning in the form of improved accuracy over time, even though some texts dealt with similar conservation context regarding specific groups of animals or threats. If the heterogeneity of the publications diminished the chance to improve rating through learning, this has wider implications: Any commonly employed preparatory exercises or training before the actual rating will be much less effective in improving the overall quality of the codes than discussions during the rating. This is in line with evidence that outcome-based feedback does not necessarily improve the accuracy of ratings, while group-based judgment for quantitative estimates seems to be more accurate and reliable than individual judgments [46].

Because of the assumed difference in underlying cognitive mechanisms of rating quantities (a skill that can be trained and calibrated) and detecting cues in text (which depends on prolonged concentration and attention to detail), we believe there are also differences in dealing with the collected quantitative and qualitative data. A commonly used strategy for dealing with divergent rater assessments in expert elicitation and modeling contexts is to compute answer averages [8,13,18,19,48,49]. Unfortunately, qualitative categories do not lend themselves to averaging due to their fuzziness.

Although errors in codes of qualitative categories cannot be smoothed out through aggregation as is the case for quantitative estimates, a non-mathematical smoothing effect might be produced through the sharing of arguments and evidence, which enables raters to adjust their best attempt to choose a fitting variable category code [46]. The difference between quantitative and qualitative content might also explain why we found a decrease in percent agreement with increasing group size, which is the opposite effect of numbers of raters on agreement in Marcoci et al. (2019). While our study investigated latent pattern content (detection of presence in context), Marcoci et al. investigated projective content (assessment/judgment of quality expressed through ordinal scales), which has more similarities to quantitative data and can benefit from mathematical smoothing effects.

Caveats of this study

Limited number of assessed publications and qualification of additional raters. When using the difference in error rates as an indicator of the reliability of the main rater, results will depend on the quality of the additional raters. Additional raters need to have sufficient education to understand the task and the content of the texts, and the necessary rigor for a successful rating experiment. In our case study, three raters were in the mid or end phase of their Bachelor's degree, and one rater was in the final stages of their Master's degree. The main rater was a PhD candidate. It is reasonable to assume that the main rater will likely have spent more time reading and thinking about the question and the coding scheme, as well as being emotionally more invested in a quality result. However, it is also reasonable to assume that more senior scientists that fit the profile of an additional rater for the coding task might be less often available and interested in taking part in such a time-intensive and poorly paid exercise.

The limited number of our sample of 25 coded publications gives evidence of how time- and budget-intensive an orchestrated group discussion is. We used available funds (~AUD 10.000) as a primary stopping rule, and all raters were paid for individual coding and discussions with a standard hourly rate until the money was used up. We, therefore, believe the limited sample size of 25 can be justified in light of budget and time constraints [26].

Additional aspects of inter-rater-reliability were not explored here but might provide further insights. The agreement within the group of additional raters relative to the main rater's code can be used as a guide to quality. Variables that show high agreement among the group of additional raters and low agreement between individuals and the main rater could indicate problems, while variables that show high agreement among the group of raters and high agreement with the main rater could be used as a general sign of quality (see Fig S4).

Our study does not address the challenges and possible solutions to coding mistakes and uncertainty for manifest or projective content. Future studies could seek to clarify whether multi-rater discussion and calibration improve the quality of reviews based on such data. We would anticipate that whenever the production of codes involves any type of judgment and prolonged focus, there is a strong potential to reduce mistakes and improve validity of codes through discussions of underlying assumptions and reflection on the strength of evidence provided by raters.

We were not able to examine effects that different media can have on reading and focus, with clear advantages of print media for comprehension and focus [50,51]. While future studies could test the effect of reading medium on agreement rates, our results are an important reminder to any academic that comprehension of texts requires prolonged focus and mistakes that lead to poor comprehension of content can easily happen, even for seemingly obvious things like species, methods and countries included in a study.

The progress of artificial intelligence and machine learning and its potential for automatization of qualitative judgments of texts. Since this study was conducted, machine learning and artificial intelligence applications that digest text for specific purposes have accelerated in their development and application. However, generative AI and chatbots make mistakes, too, and suggest for example citations that do not exist or code that does not work. Such errors are often referred to as "hallucinations". While problems like hallucinations persist and high accuracy at scale required for most academic work has not been achieved yet, programs become progressively better in text-related tasks, especially extraction of information from text [52–55]. Despite the persisting challenges, researchers see an increasing role of AI in research and for reviews in particular [56]. Future studies could compare results across human and electronic raters to assess and monitor if and when these tools will be of the needed quality to apply for contextual classification tasks.

Conclusion

Our work provides further evidence that extraction of qualitative data from free-flowing text is a demanding task and benefits from the attention of multiple people. Discussion improves agreement when multiple people interpret the same text by reducing mistakes. The positive effects of discussion on rates of agreement and patterns of error rates were clear and consistent across all variables and raters.

In light of our results, we highly recommend including a targeted inter-rater-reliability test in any classification task from text that goes beyond kappa statistics. Some issues of classification are not related to specific coder experience or skill but are inherent in free-flowing text documents, including unclear structure and terminology. Having more than one rater to compare error rates against will improve understanding of the quality of code and improve trust in quantitative and qualitative results that stem from sampling of large numbers of texts. As different types of reviews and summaries of literature are specifically part of doctoral studies, we encourage students to seek out existing additional funding sources, and Universities for providing support, to enable a systematic endorsement and best practice of conducting reviews by elevating such studies from solo enterprise to a quality checked group effort.

Supporting information

S1 File. S1A Protocol instructions. Instructions for raters on objectives of review and data entry.
(PDF)

S1 Table. S1B Table. Coding scheme cheat sheet. Full list of classification categories and explanation.
(PDF)

S2 Table. Changes made after the pilot. Details on all changes made after the pilot phase to the coding scheme including reasons.
(PDF)

S2 File. Calculations for figures.
(PDF)

S1 Fig. Average agreement across all pairs of raters compared to the main rater. S1 Fig. Average agreement across all pairs of additional raters compared to the main rater before and after each of the 6 rounds of group discussions. Discussed examples from publications were n = 1 during the first discussion, and between n = 3–5 in all other discussions.
(TIF)

S3 Table. Comparison of metrics for agreement. Kappa for individual raters and all raters, alpha for all raters, and percent agreement before and after discussion. The percent agreement after discussion differs drastically for some variables from kappa or alpha.
(PDF)

Acknowledgments

We thank the four raters, Jessica Keem, Erin Bernadette Thomas, Diego Brizuela Torres and Matthew Paul Whitney, for their participation. Thanks to Dr. Bonnie Wintle for her help in revising the coding scheme and Prof. Fiona Fidler for advice on the design of the experiment and for providing comments on the draft manuscript. Special thanks to Steven Kambouris, who helped immensely by providing advice on interrater reliability and analysis in general and providing extensive comments on the draft manuscript.

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RESEARCH PAPER
https://doi.org/10.1071/PC24057

PACIFIC CONSERVATION BIOLOGY

Decision-science navigates trade-offs between environmental and socio-economic objectives for marine debris mitigation

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Handling Editor:
Sarah Clement

Received: 5 August 2024
Accepted: 12 December 2024
Published: 13 January 2025

Cite this: Beher J *et al.* (2025) Decision-science navigates trade-offs between environmental and socio-economic objectives for marine debris mitigation. *Pacific Conservation Biology* **31**, PC24057. doi:10.1071/PC24057

ABSTRACT

Context. Marine litter is a growing global problem that impacts biodiversity and human societies alike. South-east Asia suffers significant impacts due to high biodiversity, dense human populations, and large volumes of plastics entering the marine environment, primarily through rivers. **Aims.** Drawing on decision-theory principles, Structured Decision Making (SDM) can improve site selection for marine debris management by identifying the best options to reduce plastic exposure to species, ecosystems, and human populations in the marine and coastal environment, as well as an overall reduction of drifting plastic debris in the open ocean. **Methods.** We combine an SDM framework with a plastic transport model and quantify benefits for environmental and social objectives across 542 locations covering 683 rivers along the coasts of south-east Asia in the biodiversity hotspot of the Coral Triangle. We modelled and quantified metrics for the reduction in volume and flow of plastics to all downstream coral reefs, key biodiversity areas, marine protected areas, and coastal communities. **Key results.** No location is the best option across all objectives, but the multiple metrics help to navigate trade-offs across specific objectives. Despite 95% of all plastic debris remaining in circulation in the seascape after 2 months, several rivers contribute not only large volumes of plastic debris to the overall marine pollution but also large volumes of pollution downstream. **Conclusions.** The increasing pollution of the marine environment with plastic debris can only be stopped by regulating and reducing the production of plastic products. However, as long as plastic debris is still circulating in the environment, the identification of these locations where the removal of plastic pollution will deliver the best outcomes for a set of important objectives will remain an important mitigation measure. The proposed framework effectively facilitates understanding existing trade-offs and can easily be adapted to include additional metrics or objectives. Using this framework enables decision-makers to develop a tailor-made prioritisation process for clean-up interventions in their unique socio-ecological contexts. **Implications.** This new decision-science approach for identifying efficient spatial management strategies for plastic clean-up is transferable to any geography and has the capacity to enhance local-to-global plastic management.

Keywords: clean-up intervention, conservation planning, Coral Triangle, marine debris, plastic pollution, plastic transport model, river pollution, site selection, South-East Asia, Structured Decision Making.

Introduction

Plastic debris in the aquatic environment is a growing global problem. The current levels of financial costs of marine debris to national economies are significant and create an urgent need to find ways to reduce the impact of plastic pollution (McIlgorm *et al.* 2020). Damages from marine plastic to the economies across the Asia-Pacific have risen from an estimated USD1.3 billion in 2009 to USD10.8 billion in 2015 (McIlgorm *et al.* 2020). Losses of ecosystem services linked to marine plastic debris are estimated to be around 1–5% per year, which translates to USD3300–33,000 per tonne of debris, or USD500–2500 billion per year (Beaumont *et al.* 2019).

Plastic debris has been detected at every depth, from the surface down to the sediments of rivers and oceans (Williams and Simmons 1997; Cable *et al.* 2017; Lebreton *et al.* 2017; Bauer-Civiello *et al.* 2019; Choy *et al.* 2019; Barrett *et al.* 2020). Plastic debris entering the sea generally consists of a mix of micro and macro debris, with all pieces degrading over time (Chubarenko *et al.* 2020). All size classes of marine debris have the potential to interact with species and ecosystems, including injury and death (Wright *et al.* 2013; Fossi *et al.* 2014; Hall *et al.* 2015; Wilcox *et al.* 2015; Horton *et al.* 2017; Avery-Gomm *et al.* 2018*a*, 2018*b*; Lamb *et al.* 2018; Duncan *et al.* 2021; Pinheiro *et al.* 2023). In addition to the direct impact of plastic debris, there is a range of indirect impacts on ecosystems and species (Rech *et al.* 2018*a*, 2018*b*; MacLeod *et al.* 2021), and social values, including ecosystem services and human health (Beaumont *et al.* 2019; Campbell *et al.* 2019; Ragusa *et al.* 2021; Danopoulos *et al.* 2022).

Plastic production and pollution caused by mismanaged waste are projected to increase dramatically by 2030, resulting in over 6.3 billion tonnes of plastic waste being produced (Borrelle *et al.* 2020). Of the 20 million tonnes of plastic debris currently entering aquatic systems annually, 1.15–2.41 million tonnes enter through river systems (Lebreton *et al.* 2017; Borrelle *et al.* 2020). Active waste removal will remain essential to mitigate the impact of plastic debris leaking existing waste management streams into terrestrial and aquatic environments. However, there are limited resources to implement plastic waste removal, so understanding where the most effective places are to deploy removal efforts is essential.

Many studies quantify the volume of plastic debris that enters the aquatic environment (Geyer *et al.* 2017; Lebreton *et al.* 2017; Borrelle *et al.* 2020) and identify where it accumulates within the water column (Reisser *et al.* 2015; van Sebille *et al.* 2015; Hardesty *et al.* 2017; van Sebille *et al.* 2020). Other studies address the processes of prioritising the locations to remove large volumes of debris from the open ocean most efficiently (Sherman and van Sebille 2016). However, understanding the pathways from the source to the downstream sites where pollution impacts biodiversity and society is an emerging important field of research (Tessnow-von Wysocki *et al.* 2023). Despite promising first publications (Compa *et al.* 2019; Critchell *et al.* 2019), much more work is needed to include all relevant components of the problem. To better manage the plastic problem, we need the capacity to predict the entire plastic pathway, from the source of plastic debris entering the environment to the various downstream habitat destinations where the ecological and social impacts arise. Currently, no framework exists to quantify the predicted inflow of plastic debris to specific habitats downstream of the source of debris when selecting places for clean-up actions.

National governments, non-governmental organisations (NGOs) and local communities need to identify locations where the removal of plastic debris is feasible but also where the investment of time and budget are well justified. In many regions, thousands of locations can be selected for clean-up activities across the considered seascape. Assessing them all in detail is not possible and often, specific criteria are used to narrow down the options in a strategic way. Most plastic removal projects base their clean-up site selection on local characteristics, such as the existing volume of debris, the likelihood of waste mismanagement, local economies, and the level of support and motivation of local government (for example, https://plasticbank.com, https://theoceancleanup.com, https://ghostdiver.com, https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup, https://seabinproject.com, https://cleancurrentscoalition.org, https://www.tangaroablue.org, https://marinedebris.noaa.gov/our-work/prevention, https://cleancurrentscoalition.org).

Unfortunately, none of these efforts use a formal prioritisation process based on sound decision-theory criteria and therefore lack the ability to consider the trade-offs between different objectives. A strategic site selection process that draws on insight from decision science can maximise positive outcomes for the environment and communities while minimising costs (time and money spent). A well designed site selection process can also capitalise on spatially explicit planning, robust decision science, and transparent risk analysis (Burgman 2005; Moilanen *et al.* 2006; Sarkar 2012; Widis *et al.* 2015; Sherman and van Sebille 2016).

The framework of Structured Decision Making (SDM) (Gregory *et al.* 2012) has been developed to guide difficult decisions for environmental management and addresses many shortcomings of *ad hoc* prioritisation procedures (Game *et al.* 2013). The framework is also one important strategy to overcome the barrier of uncertainty when trying to inform policy (Rose *et al.* 2019), offering distinct steps that provide a transparent process of value-driven prioritisation (Fig. 1). In this paper, we apply SDM and spatially-explicit plastic debris modelling to achieve three main objectives:

1. Demonstrate the power and utility of Structured Decision Making in aiding in the marine plastic debris problem,

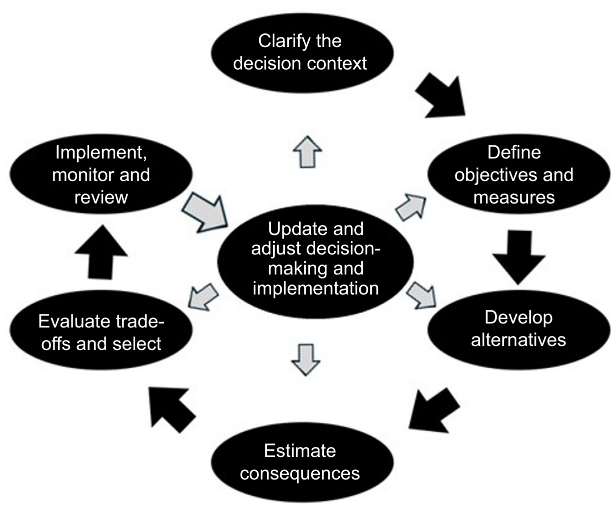

Fig. 1. Structured Decision Making follows a stepwise planning strategy with the potential to feed gained insights back into future decisions of the same type. Adapted from Gregory *et al.* (2012).

2. Create novel and quantitative metrics for evaluating the impact and feasibility of active debris removal, and
3. Illustrate this approach across the Southeast Asian seascape characterised by high biodiversity, dense human population, and high volumes of plastic pollution.

Our research provides a blueprint on how to conduct a value-based site selection process for marine plastic mitigation in the form of clean-up interventions, including multiple social and ecological objectives and navigating trade-offs and co-benefits (Keeney 1992; Halpern *et al.* 2013).

Materials and methods

We apply the six steps of Structured Decision Making (SDM) (Fig. 1) to the problem of prioritising sites for removing plastic debris before it flows into the sea through clean-up interventions at source rivers (Silva *et al.* 2021). Below, we briefly describe each step of our application of SDM and then provide more details in subsequent sections.

Scoping of the decision context

We expand the scope of current mitigation strategies that focus on volume reduction through clean-ups and include a focus on the downstream impact from specific sources. Our study is in south-east Asia, a global hotspot for population, pollution, and biodiversity. Over 90% of the global plastic discharge from rivers into the ocean comes from 122 rivers, of which the vast majority are located in this area (Lebreton *et al.* 2017). South-east Asia has also been identified as a global hotspot of oceanic plastic accumulation (Onink *et al.* 2021). The seascape around the Coral Triangle and the shoreline between the Bay of Bengal and the East China Sea (Fig. 2) is exceptionally biodiverse (Roberts *et al.* 2002). The population density in Asia is higher than in other parts of the world, and many Asian countries receive plastic imports from the international plastic waste industry, despite an often problematic waste management situation (Liang *et al.* 2021). The combination of large volumes of debris, high population density and high biodiversity creates the potential for high negative impacts. Conversely, there are also significant opportunities for interventions such as clean-ups, as well as likely trade-offs or co-benefits between environmental and socio-economic objectives. The UN listed the exploration of plastic debris trajectories within the seascape as one of the key challenges for the coming years. Furthermore, the movement and fate of plastic debris have emerged as one of the five most important research priorities for stakeholders in south-east Asia, along with environmental and socio-ecological impacts, possible solutions, description of pollution and regional policies (Omeyer *et al.* 2022).

Our methods provide a quantitative overview of the key trade-offs for possible clean-up locations, helping to navigate the different benefits for ecological and social objectives and the political feasibility of implementation based on the geopolitical locations of source rivers and receiving sites (Galaiduk *et al.* 2020). Intercepting debris at a place with a small spatial footprint, like a river, is more cost-effective than targeting debris that has already reached the ocean (McIlgorm *et al.* 2020). As a result, The Clean Currents Coalition has launched an investment of 11 million dollars for trialling different methods to remove debris in nine rivers around the world (Silva *et al.* 2021), four of which are located in Asia.

Communication during the scoping phase of this modelling project validated the relevance of metrics and objectives for agencies that plan and conduct debris removal actions (personal communications with staff from Benioff Ocean Initiative and associated partners).

Defining objectives and metrics for site selection of mitigation actions

Clear and quantifiable objectives are essential for a targeted risk reduction of exposure of plastic debris to society and biodiversity. Candidate performance measures need to capture two relevant aspects of impact of a hazard like plastic debris, the type and the risk, in a clear and quantifiable way. The hazard type includes the presence of people and biodiversity that are susceptible to a negative impact at these sites. The likely exposure risk accrues from the volume of plastic debris and the passive transport routes from the river mouth to downstream sites.

Value-based objectives

The development of all relevant objectives require the consultation of key stakeholders in order to understand the values that matter in the decision-making process (Keeney 1992; Gregory *et al.* 2012). For example, communities likely value the onsite benefits of reduced exposure to plastic debris in their direct vicinity. However, NGOs and governments might also value comparing local impacts and ensuring equity across a larger region, and considering the feasibility of clean-up interventions as well as likely impacts downstream.

Here, we assume that the reason to mitigate marine plastic debris is to prevent a negative impact on both biodiversity and human society, while acknowledging that the feasibility of local clean-up interventions will vary for technical and political reasons. As a result, these assumptions require the development of multiple objectives.

Biodiversity is seen as valuable for its intrinsic value as well as its contribution to people in the form of ecosystem services. We defined ecological value through biodiversity and conservation-related features, such as species or habitats that are known to suffer negative impacts from plastic debris, in particular coral reefs, marine protected areas and key biodiversity areas. The related objective is to reduce the impact of plastic pollution on the currently existing features.

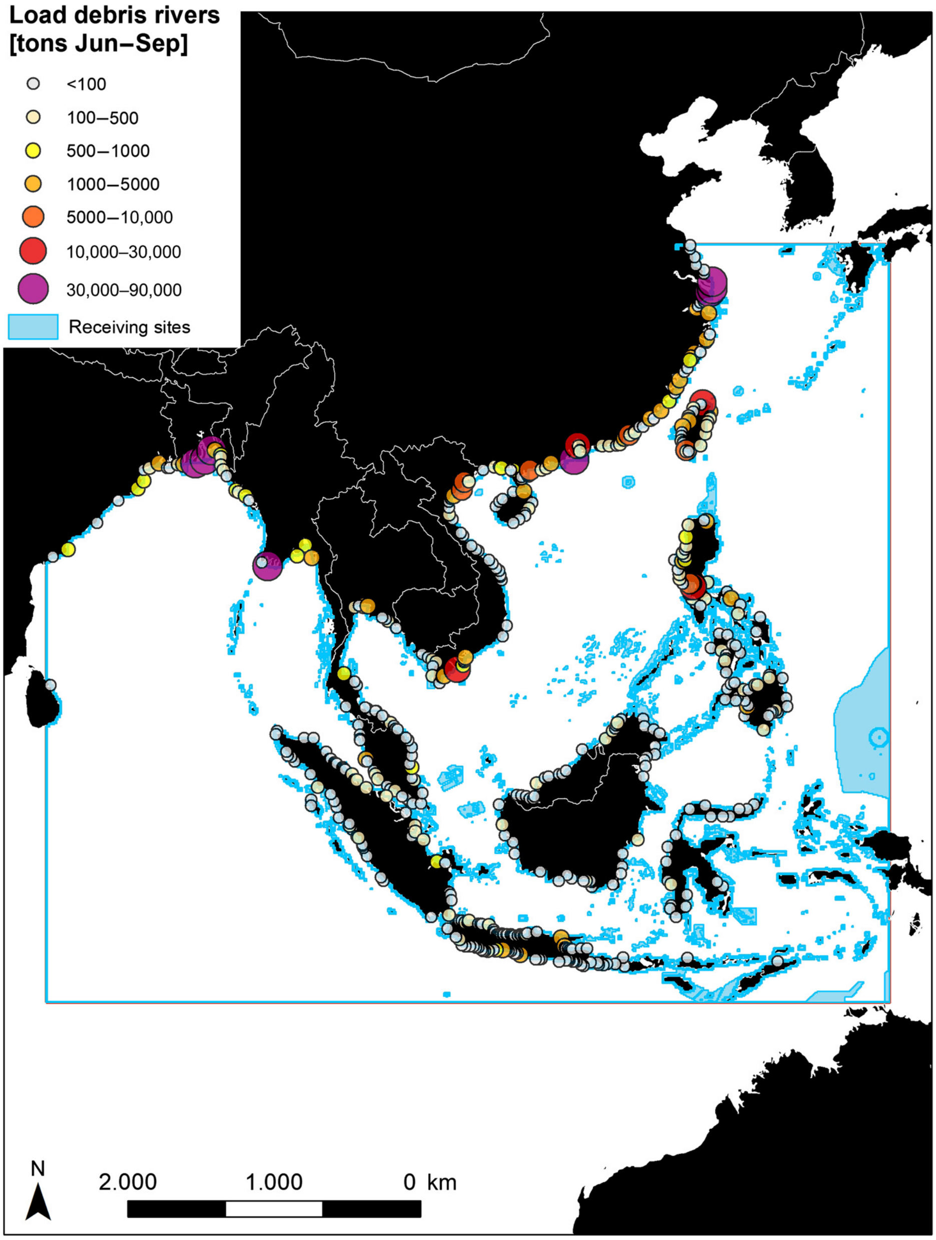

Fig. 2. Model domain in the Indian and Pacific Ocean. Receiving sites were delineated using available spatial data for coral reefs, marine protected areas, key biodiversity sites, and general coastline (UNEP-WCMC, WorldFish, World Resources Institute, The Nature Conservancy 2010; Birdlife International 2020; UNEP-WCMC and IUCN 2021). Volumes of plastic debris in rivers (symbolised by points) were summarised from Lebreton *et al.* (2017).

Demographic groups that live in polluted areas and depend on subsistence fisheries are particularly at risk of a negative impact of plastic debris on health and well-being. Large parts of the population in the Coral Triangle and south-east Asia depend highly on coral reefs (Burke 2011). Therefore, we quantify social value using population density as a proxy (Center For International Earth Science Information Network-CIESIN-Columbia University 2017). The related objective is to reduce the impact of pollution for as many people as possible.

Regarding technical and political constraints, we included two aspects of logistics: (1) minimise the number of rivers that would need to be cleaned to reduce the volume of inflowing plastic debris; and (2) minimise the political complexity related to the number of jurisdictions that are exposed to plastic pollution from a particular source (Galaiduk *et al.* 2020).

Based on these assumptions, we adopt the objectives of 'maximise the benefits (for each of the socio-economic and environmental metrics), while minimising the constraints (feasibility-related metrics)' to identify source rivers where management actions and clean-ups could be implemented. We developed multiple metrics to capture the important nuances of these objectives.

Metrics for impact and feasibility

The contribution of clean-up actions towards our different objectives depends on how the impact is measured. We developed multiple metrics to capture the nuances of site-specific impacts of different clean-up locations at the source (Table 1). For site-specific impact downstream, two metrics of pollution were used: reduction expressed in total volume and expressed as a percentage. Both are needed to make an informed choice of relative benefits that a local clean-up intervention would provide. For example, when comparing two options that reduce the same amount of downstream pollution, the percentage can inform if the difference is likely of broader social and ecological relevance. At the same time, when two options provide the same percent reduction at a downstream site, the amount of volume can identify the more valuable option. As a transparent benchmark, we considered downstream impact within 2 months of plastic release, acknowledging the potential long-term benefits of reducing the volume of plastic debris at the source.

In summary, trade-offs are expected between the *precent reduction* and total *volume of reduction* of pollution impacting individual downstream sites, the *sum of all reduction across all downstream sites* and the *reduction of total plastic entering at the source*. To quantify the magnitude and type of impact that a management action can have, and identify key trade-offs, we investigated 14 different metrics across four objectives (Table 1). The exact method to calculate more complex metrics is described in section *Estimate consequences of alternative management actions* in subsection *Calculation of ecological impact*.

Develop realistic alternatives

Across our study area, we use all major river mouths as potential plastic sources and management opportunities. We only included major rivers with a minimum input of 65 tonnes per year (Lebreton *et al.* 2017) to justify investment in long-term management (Benioff Ocean Initiative 2019), which resulted in 683 rivers in the region included in the model. These 683 rivers are estimated to discharge 700,000 tonnes of plastic into the ocean between June and September of each year (Lebreton *et al.* 2017). These volumes and time periods for all rivers were included in the model. For the Rivers Ganges and Yangtze with estuaries wider than 100 km, we divided the discharge among three equidistant points along the estuary to represent the geographic variation in flow. In total, 542 source cells in the model domain contained river mouths with plastic where clean-up interventions could take place resulting in downstream impacts.

Table 1. Performance measures for different objectives that were utilised to compare the impact of different actions and identify key trade-offs.

Objective	Metric	Sub-objective (habitat types)
General impact statistics	(t) Impact at source river, see Eqn 4	
	(t) Downstream impact across all sites, see Eqn 3	
	(%) Fraction of the river load that pollutes sites across system	
	(n) Sites impacted by this source	
	(km^2) Area impacted (across all sites)	
	(n) Sites this source is the main source of pollution	
Impact for environmental objectives	(t) Volumetric impact downstream, see Eqn 2	Reef
		KBA
		MPA
		Coast
	(%) Reduction in pollution across sites and area, see Eqn 1	Reef
		KBA
		MPA
		Coast
	(n) Sites with reduced pollution	Reef
		KBA
		MPA
		Coast
	(km^2) Area with reduced pollution	Reef
		KBA
		MPA
		Coast
Impact for social objectives	(n) Impact of a river on number of people within 8 km^2 vicinity	
	(n) River as main source of pollution for number of people within 8 km^2 vicinity	
Feasibility	(n) Technical feasibility: number of source rivers with large contribution to site pollution, width of estuary	
	(n) Political feasibility: number of EEZ impacted	

KBA, key biodiversity area; MPA, marine protected area.

Estimate consequences of alternative management actions with a plastic transport model

To quantify the consequence of clean-up intervention at all 542 locations, we calculated the 14 impact metrics aligned with our objectives (Table 1) by tracking the passive transport of plastic debris through ocean currents from these source locations through the seascape. We developed a plastic transport model to quantify downstream impact. We provide a more detailed description of data preparation in the Supplementary material S1.

The model domain

The model domain (Fig. 1) was divided into a grid of 721 × 649 cells with an 8-km × 8-km resolution. We used publicly available spatially explicit data on reefs, protected areas and key biodiversity areas to create distinct sites of biodiversity value within the seascape (UNEP-WCMC, WorldFish, World Resources Institute, The Nature Conservancy 2010; Birdlife International 2020; UNEP-WCMC and IUCN 2021). Values for the area of all occurring features (coastline, reef, marine protected area, and key biodiversity area) were extracted for each cell, split for unique combinations of overlap, such as individual features (for example, the area covered by a reef), or any combination (for example, the area covered by a reef within a protected area). Neighbouring cells containing the same type of environmental features were aggregated to sites with a unique ID number. We included the general coastline in the delineation of sites as coastal areas function as a general sink for marine debris (Martin *et al.* 2020; Schernewski *et al.* 2020). This resulted in 4444 sites that could receive inflowing plastic debris. Of these, 617 sites contained key biodiversity areas, 1047 protected areas, 1701 reef, 2922 coastline, and 10 sites represented the borders of the modelled seascape. We assigned a social value to each site by extracting gridded population density within the boundaries of each site. We added the habitat properties and human population of a surrounding one-cell neighbourhood for each individual site to deal with the inherent limitation of cell size and placement of grid cell walls. Because of these limitations, results are not meant to be used at the scale of individual receiving sites but need to be interpreted at a more regional scale.

Plastic transport model

We developed a spatially explicit advection-transport model to quantify the impact of implementing clean-up actions at each of the 542 source rivers on pollution of the source site itself, the ocean, or downstream sites. Our model was based on: (1) the location of the rivers as the source of plastic debris; (2) the downstream sites for which inflow should be measured described in section *The model domain*; (3) the volume of debris that the source rivers discharge into the sea; (4) the characteristics of floating particles; (5) the dates of specific release events; and (6) drift time duration.

Over 70% of the debris carried by rivers to the Asian seascape each year gets discharged between May and October (Lebreton *et al.* 2017). We released a cloud of virtual plastic debris from each source river during each week of the months of June, July, August, and September for each year between 2005 and 2015, matching the time frame of the published debris data (Lebreton *et al.* 2017).

Following the release of the cloud of plastic debris, it was allowed to be transported downstream by ocean currents. We tracked the clouds of virtual plastic debris in 3-hourly time steps through the flow field (Treml *et al.* 2012, 2015; Waruszewski *et al.* 2018, see Supplementary material S2). Whenever any fraction of debris released from a source reached a receiving site, a connection between the source and the receiving site was recorded.

Model parameters of local-scale turbulence and the entrapment rate determined how much debris was caught on downstream habitat patches after a minimum drift time of 12 h to avoid overemphasis on settlement at the source locations. The entrapment rate included any interaction with wildlife, such as intake or entanglement, or settlement on habitats or beaches. Each simulation was stopped 60 days after the release date, and all debris ending up on downstream sites was tallied. We used a travelling period of up to 60 days to identify strong short-term impacts of pollution. A pilot run indicated travel distances over 2000 km are possible within this time frame. All recorded connections between source rivers and downstream sites of value within the tracked 60 days were recorded in a connectivity matrix and used for further analysis (see section *Calculation of ecological impact*).

Due to uncertainty in the volume of plastic inflow, entrapment rate, and the specific depth of debris in the water column during travel time in the ocean, we performed a simple sensitivity analysis with eight scenarios. Uncertainty around the volume of plastic debris in the source rivers was explored in one scenario for average and one scenario for high model estimates (Lebreton *et al.* 2017). Uncertainty around the depth of debris in the water column and the entrapment rate is a consequence of the variety of sizes and shapes of different items in a cloud of debris.

The uncertainty around the specific depth of plastic particles in the water column stems from the unknown composition of different sizes and buoyancy of plastic debris items. All size classes, from macro to nano debris, are likely to be present in the rivers at any point in time. In addition, the composition of different size classes will change over time as the shedding of smaller particles is an ongoing process. Knowledge of how particle size and shape determine the floating and mixing behaviour of individual units of debris in the water column can inform the choice of ocean current data at a specific depth (Chubarenko *et al.* 2016; Khatmullina and Chubarenko 2019). This uncertainty was explored with two scenarios: one using currents in the surface only (top 1 m), and a second using the top 25 m from the HYCOM ocean circulation model (Chassignet *et al.* 2007).

The uncertainty about how much debris was caught on downstream habitat patches was explored through one scenario assuming a higher entrapment rate of 30% per day and one scenario with a lower likelihood of 2% plastic settlement per day. The ensemble of eight scenarios produced source-to-destination links of marine debris for every release from every river for all weeks across all years.

Calculation of ecological impact

Based on the output of the advection transport model output, we calculated four metrics related to different strategies of prioritisation of clean-up interventions at source rivers (Eqns 1–4, Fig. 3).

1. Relative Impact (Eqn 1)
   Prioritise source rivers that contribute large *relative* amounts of pollution to specific receiving sites by calculating the relative contribution this river made to the total pollution of any specific receiving site.

$$\text{Relative impact receiving site } [\%] = \text{Inflow from river}_i \text{ at receiving site}_j / \text{Total inflow from all rivers}_{i:n} \text{ at receiving site}_j \times 100 \quad (1)$$

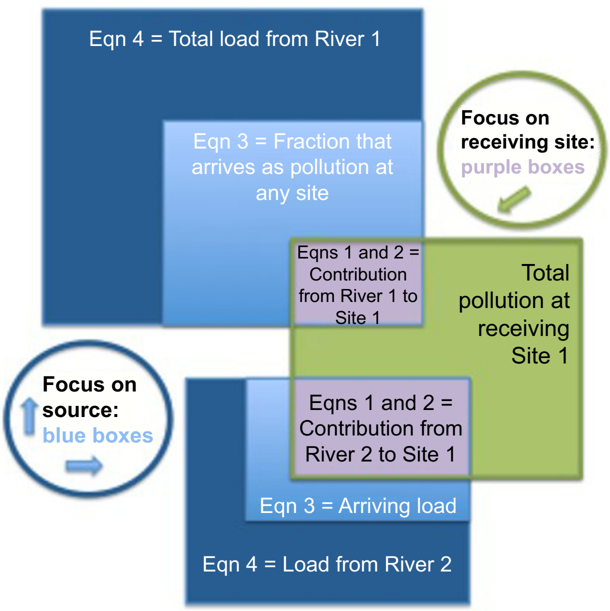

Fig. 3. Example of metrics for different strategies to reduce the impact of plastic debris. Current mitigation planning focuses on source-centric metrics (in blue). Our study highlights the importance of including metrics for a specific type of impact downstream of the source of pollution. The conceptual diagram highlights that destination-centric metrics will rank sources based on a much smaller fraction of their total pollution load by counting only the volume of pollution accumulating at places of value. Each river is modelled with a specific total load of debris (Eqn 4), of which a specific fraction arrives via passive drift at a destination site within the modelled time (Eqn 3). Most sites receive debris from multiple rivers. Therefore, the contribution of a river to a specific site can be calculated as the contribution in percent (Eqn 1) or volume (Eqn 2) of one source to the total inflow of pollution at this specific receiving site.

2. Volumetric Impact (Eqn 2)
   Prioritise source rivers contributing a large volume (metric tonnes) to specific receiving sites by calculating the contribution this river makes to the total pollution of any specific receiving site.

$$\text{Impact receiving site } [\text{t}] = \text{Inflow from river}_i \text{ at receiving site}_j \quad (2)$$

3. Total downstream Impact (Eqn 3)
   Prioritise source rivers contributing a large volume to the total downstream pollution across all receiving sites by summing up arrivals across all downstream sites.

$$\text{Impact across all receiving sites } [\text{t}] = \Sigma \text{ Inflow from source river}_i \text{ across all receiving sites}_{j:n} \quad (3)$$

4. Impact at source and open ocean (Eqn 4)
   Prioritise source rivers with high load of debris by using available data on loads of plastic pollution in metric tonnes.

$$\text{Source river pollution } [\text{t}] = \text{load of plastic debris of source river}_i \quad (4)$$

We calculated each metric for the three environmental objectives (reduce the impact on reefs, protected areas and key biodiversity areas). For each source river, we could identify all downstream sites with the occurrence of each habitat type and the quantities of pollution that would accumulate there. Based on this information, we subset and ranked individual source sites for relative and volumetric impacts on each habitat type.

Calculation of social impact

We expanded on the metrics for ecological impact to calculate the expected social impact by discounting Eqns 1–3 based on the relative number of people who would benefit from reduced exposure to pollution at each receiving site. Population density data were derived from a 5-km × 5-km grid of global population densities and summed up for an 8 km buffer around each receiving site. The size of the buffer equates to an expansion of each site of one additional grid cell into all directions, under the assumption that people in poverty who depend most on fishing and other ecosystem services can access the coastline within 8 km on foot on a daily basis (Burke 2011), and people visit closer sites more likely in their leisure time than sites that require longer travelling. Population density was relativised to the maximum value across sites in the seascape (240.595 people per km^2 at one site). The social impact at receiving sites was calculated by multiplying impact metrics for biodiversity at these sites (metrics 1–3 above) by the relative population density within 8 km.

Feasibility related metrics

To identify which receiving sites were most feasible to manage, we used two metrics: one related to technical feasibility and one related to political feasibility. Regarding technical feasibility, we assumed that the less source rivers need to be cleaned up to reduce the inflowing plastic debris at a receiving site to a desired level, the less infrastructure and resources would be required to establish long-term management for waste removal. Therefore, we used the number of source rivers as a metric for technical feasibility.

We defined political feasibility as the *trans*-jurisdictional impact of debris dispersal and measured it by overlaying the impacted receiving sites of each source river with a map of the world's Exclusive Economic Zones (Flanders Marine Institute (VLIZ), Belgium 2019). The overlay returned the number of countries that would be involved when managing the source of plastic debris to reduce impact at individual receiving sites, which we used as metric for political feasibility.

We discuss the implications for regional and international management options under the assumption that management for polluted sites is easier when fewer rivers contribute a large fraction of the total pollution at a receiving site and the source is located in the same jurisdiction. For our case study, we used the number of main pollution sources to the most polluted downstream sites in an intermediate step for selecting the most promising locations for clean-up interventions (see Supplementary material S3 and S4). The number of countries involved in planning and implementing a clean-up at relevant sources was used as a metric in the consequence table assessing the trade-offs between the selection of most promising locations (Tables 1 and Supplementary material S3 and S4).

Summarising impact using network analysis

Most metrics needed specific parameters to be calculated, which we produced using network analysis. Our networks consist of a set of nodes representing source rivers and receiving habitats or sites, and all the connections between them representing the volume of plastic flow from sources to destinations. Each scenario returned a set of adjacency matrices that showed: (1) the probability of a connection between a source node and a receiving site downstream; and (2) the relative volume of debris that drifted from each source to each receiving location.

The different matrices were used to create the network model depicting the source-destination dynamics of plastic debris across our seascape (Urban and Keitt 2001; Treml *et al.* 2015). We used the package *igraph* (Csardi and Nepusz 2006) in the software R (R Core Team 2020) to complete all network analysis (Fig. 3, Eqns 1–3).

The following parameters in our impact metrics were derived from the plastic transport model (see annotated R-code on figshare and Supplementary material for more details):

1. The probability of a connection between a source point (river mouth) and a receiving site. A connection was recorded whenever plastic particles from a source reached any receiving site location. The output is an adjacency matrix containing values for the probability of a connection. This parameter was used in the calculation for metrics regarding downstream impact in volume and percent of pollution.
2. The inflow of all debris from each source river to each individual destination site in tonnes per year. This metric was used to identify sites that receive large quantities of debris from specific rivers. The output was an adjacency matrix containing values for the strength of a connection.
3. The count of how many source rivers contribute to the pollution of each receiving site. The count was produced by summarising source locations for each receiving site from the adjacency matrices.

For the calculation of feasibility metrics, we derived:

4. The count of how many downstream sites receive inflowing debris from each source river. The count was produced by summarising destinations for each source river from the adjacency matrices.

Evaluating trade-offs to prioritise clean-up locations

The set of impact metrics allows an evaluation of the inherent trade-offs and co-benefits between the reduced impact on biodiversity, reduced impact on the coastal population, reduced inflow of debris into the ocean, and feasibility-related characteristics of clean-up sites. In order to evaluate key trade-offs and assess how assumptions and objectives impact the ranking of clean-up locations, we used a consequence table, which is a standard tool within SDM (Gregory *et al.* 2012). The table shows how well the alternative clean-up sites satisfy each objective and metric, highlighting the trade-offs across objectives. We present results from the average modelled flow across all release events in all years, depths, and settlement rates, for the average modelled load of rivers and a drift time of 60 days.

Implementation and monitoring

Through the framework presented here, managers across the seascape have the capacity to efficiently identify optimal management actions for reducing the impact of plastics. Although this sixth step is outside the scope of this study, management authorities can use the provided information, maps and concepts to understand the complexity of different options. Once they have made a choice and implemented a clean-up intervention at a site, they can re-enter the decision process with new information whenever monitoring results indicate that the expected benefits are not achieved, enabling a more adaptive management approach.

Results

Sixty days after entering the ocean during each release across all source rivers, the vast majority of the 700,083 metric tonnes of plastic debris remained adrift in the modelled seascape, 34,433 tonnes (5%) had entered receiving sites downstream, and only 641 tonnes had drifted out of the domain. The transport model identified 120,479 individual connections between source rivers and downstream sites with substantial differences in the volume of debris (Supplementary material S2 Fig. S1).

Ranking source rivers in parallel for each metric highlights not only locations that have a high impact for individual objectives but also those that rank high for multiple objectives. The parallel ranking can quickly narrow down options to a manageable quantity that deliver high impact for one or more objectives (Supplementary material S3 and S4).

Identifying locations for high impact mitigation actions

The parallel ranking and the comparison of the individual metrics for sources in general and main sources for most polluted sites in particular highlighted several sources for which clean-up interventions could provide large benefits for several objectives. In the following, we provide further detail of the decision process comparing multiple criteria for each of the following options for clean-up locations: the Modaomen Shudao Channel and the Yangtze River in China; the River Ganges in India and Bangladesh; the Irrawaddy River in Myanmar; the River Song Hau in Vietnam; and the Pasig River in the Philippines.

The Modaomen Shudao Channel in China (#146) provides co-benefits for all objectives except for the total sum of inflowing debris across all downstream sites. The channel carries the third largest load of pollution in the seascape. The three source points in the Yangtze River estuary (ID #195, 196 and 197) and the source points from the estuary of the River Ganges (#15, #16 and #17) carry the largest volume of plastic debris (impact at source, Eqn 4), but are not among the most relevant rivers for coral reefs or overall contribution to downstream pollution (Supplementary material S3).

The River Song Hau in Vietnam (#95) and Irrawaddy River in Myanmar (#29) rank highly for all objectives except for the total sum of inflowing debris across all downstream sites and either Key Biodiversity Areas or Marine Protected Areas. The Pasig River in the Philippines (#255) has the highest rank for impacting coral reefs, both for the most polluted reef site as well as pollution across all impacted reefs, and also ranks high in terms of volume of debris. Coral reefs started to appear from rank 45 of the most polluted sites (Supplementary material S4), where a small reef of 2.4 km^2 within a site of 320 km^2 in the Philippines was polluted by an annual inflow of 159 tonnes of plastic debris by the Pasig River draining into the Bay of Manila. The high value of coral reefs for biodiversity and many coastal communities can be used to justify the inclusion of the most important source of pollution for this ecosystem despite the lower ranking for some other objectives (Supplementary material S3).

Mapping the trajectories of plastic debris from all source rivers to all downstream sites shows clear geographical patterns, with several sources standing out that impact the seascape with large volumes of debris over larger distances (Fig. 4). Tailor-made maps can help to understand the context for specific objectives. For example, mapping the top 30 sources, pathways, and impacted sites for different objectives (Tables S1 and S2 in Supplementary material S3 and S4) highlights differences and similarities between the different metrics (Fig. S2 Supplementary material S3) or habitat types (Fig. S3 Supplementary material S3).

The top 30 rivers that carried the highest load of debris (*impact at source*) were distributed in seven countries: the mainland in China, Taiwan, Thailand, India, Bangladesh, Myanmar, and the Philippines (Supplementary material S3, Fig. S2, panel a). The 30 rivers that contributed the most to downstream site pollution (*total downstream impact across all sites*) were distributed in five countries because the rivers with high load in India and Thailand were not contributing as much to downstream pollution compared to several additional rivers in China and Taiwan (Supplementary material S3, Fig. S2*b*). The most polluted sites (*volumetric impact*) were strongly clustered along the coast of Myanmar, Bangladesh and China, around the three rivers with the largest loads (Ganges, Yangtze, and Modaomen Shuidao Channel; Supplementary material S3, Fig. S2*c*). In contrast, the sites with the highest combination of pollution and human density were found throughout the entire seascape (Supplementary material S3, Fig. S2*d*), with some important sources with less total load.

The majority of the 30 most polluted sites for reefs, marine protected areas and the general coastline were located along China's and north Thailand's coast (Supplementary material S3, Fig. S2). Important additional countries or regions were the Philippines for reefs, key biodiversity areas and marine protected areas, Myanmar for reefs, key biodiversity areas and marine protected areas, the south of Thailand for reefs, Bangladesh for all but for reefs, Myanmar for all but the general coastline, and India for Marine protected areas (Supplementary material S3, Fig. S3). Some sites with reefs, marine protected areas, and the general coastline received high loads from source rivers several hundred kilometres away. For example, #146 pollutes reefs up and down the coastline with more than 20 tonnes of debris over a distance of over 700 km and almost 60 tonnes over a distance of over 200 km. River 255 has several strong connections to reef sites with a flow between 40 and 117 tonnes.

Feasibility related metrics: discharge and benefits by country

The Yangtze River (#196) and Modaomen Shudao Channel in China (#146), the River Song Hau in Vietnam (#95), the

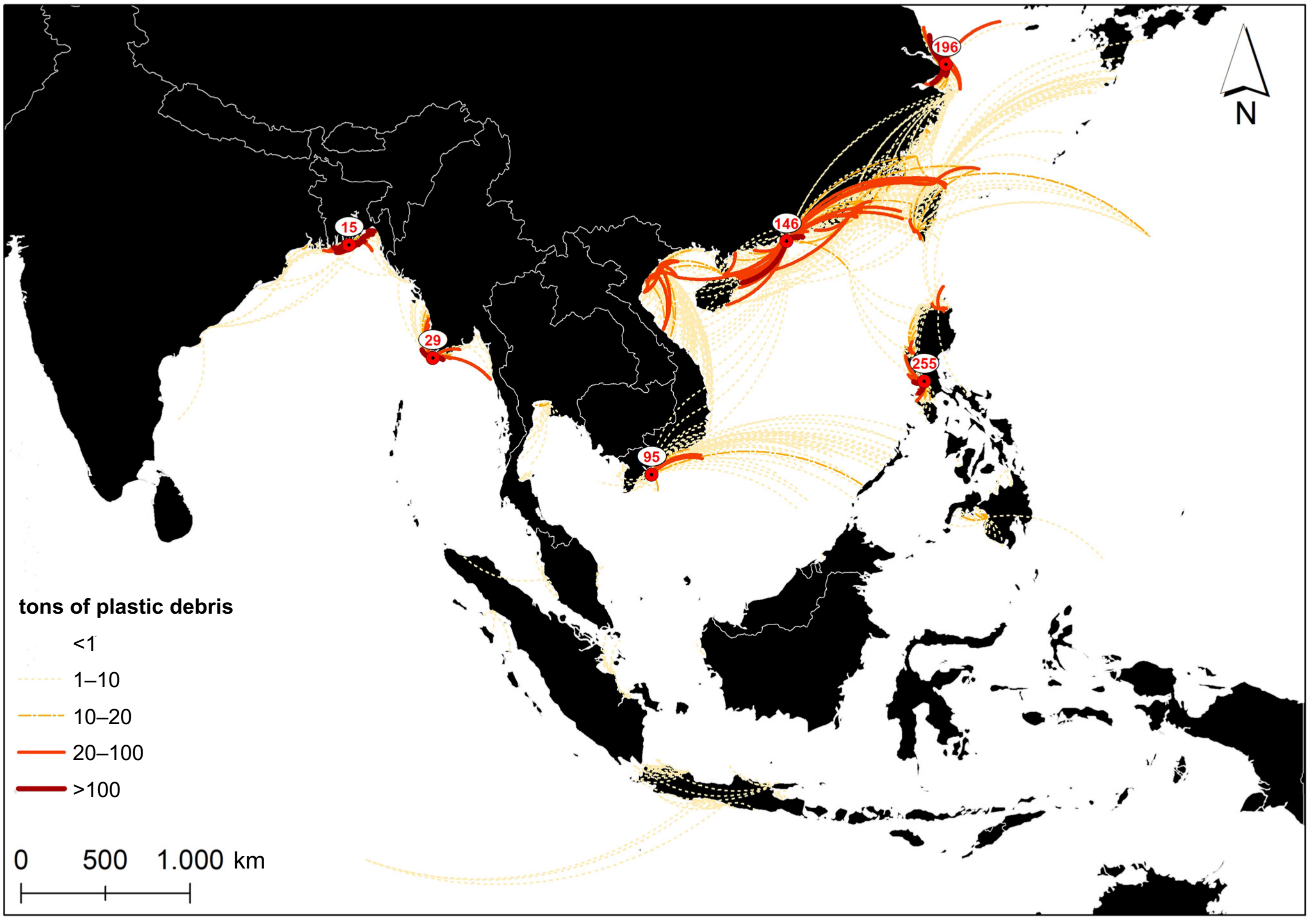

Fig. 4. Among the 542 source rivers, only a few stand out that contribute large amounts of pollution to individual downstream sites. Pollution is travelling substantial distances of several hundred kilometres within 2 months, especially along the coast of China. The six rivers that rank high for multiple objectives are all sources of the strongest pollution trajectories in the seascape, here marked up with their ID numbers. The strong pollution pathways out of the north of Vietnam are attributed to source rivers #123 and #126, which both rank high but for slightly fewer objectives than the six rivers analysed in more detail (see Table S2 Supplementary material S4).

River Ganges in India and Bangladesh (#15), the Irrawaddy River in Myanmar (#29) and the Pasig River in the Philippines (#255) all impact additional jurisdictional zones, but to very different degrees (Fig. 5). The knowledge of international connections between sources of plastic debris and impacted habitats can be a key factor in fostering collaboration and meaningful strategic regional planning not confined by borders.

For example, even though carrying one of the highest loads of debris of all rivers in the seascape, the Yangtze River pollutes only sites within two Economic Exclusion Zones (EEZs), China and South Korea, contributing large fractions to the inflowing debris at multiple sites in both countries (Fig. 5*a*).

The River Son Hau in Vietnam (source ID #95) seems to be a less feasible case to target clean-up actions (Fig. 5*b*), as the pollution from the river gets scattered across ten different jurisdictions, contributing 60–90% of the inflowing plastic debris in many individual sites. Despite the large cuts in pollution inflow, it might not be tempting for Vietnam to invest in clean-up technology when most of the benefit is gained abroad.

Several sites in India receive 60–90% of the incoming debris from the Bangladeshi side of the River Ganges delta (source ID #15, Fig. 5*c*). As the River Ganges flows through both countries and the estuary stretches across the border, there might be opportunities and incentives for joint investment. If Bangladesh would aim to intercept debris at this specific location within the estuary, it could reap the most benefits within its own jurisdiction.

Meanwhile, the Pasig River (#255, Fig. 5*d*), draining into the Bay of Manila, primarily pollutes sites of value within the Philippines' EEZ, with only weak connections to two other EEZs. Therefore, clean-ups at this location might provide a feasible and highly beneficial opportunity for this region to reduce plastic pollution levels for the environment and people.

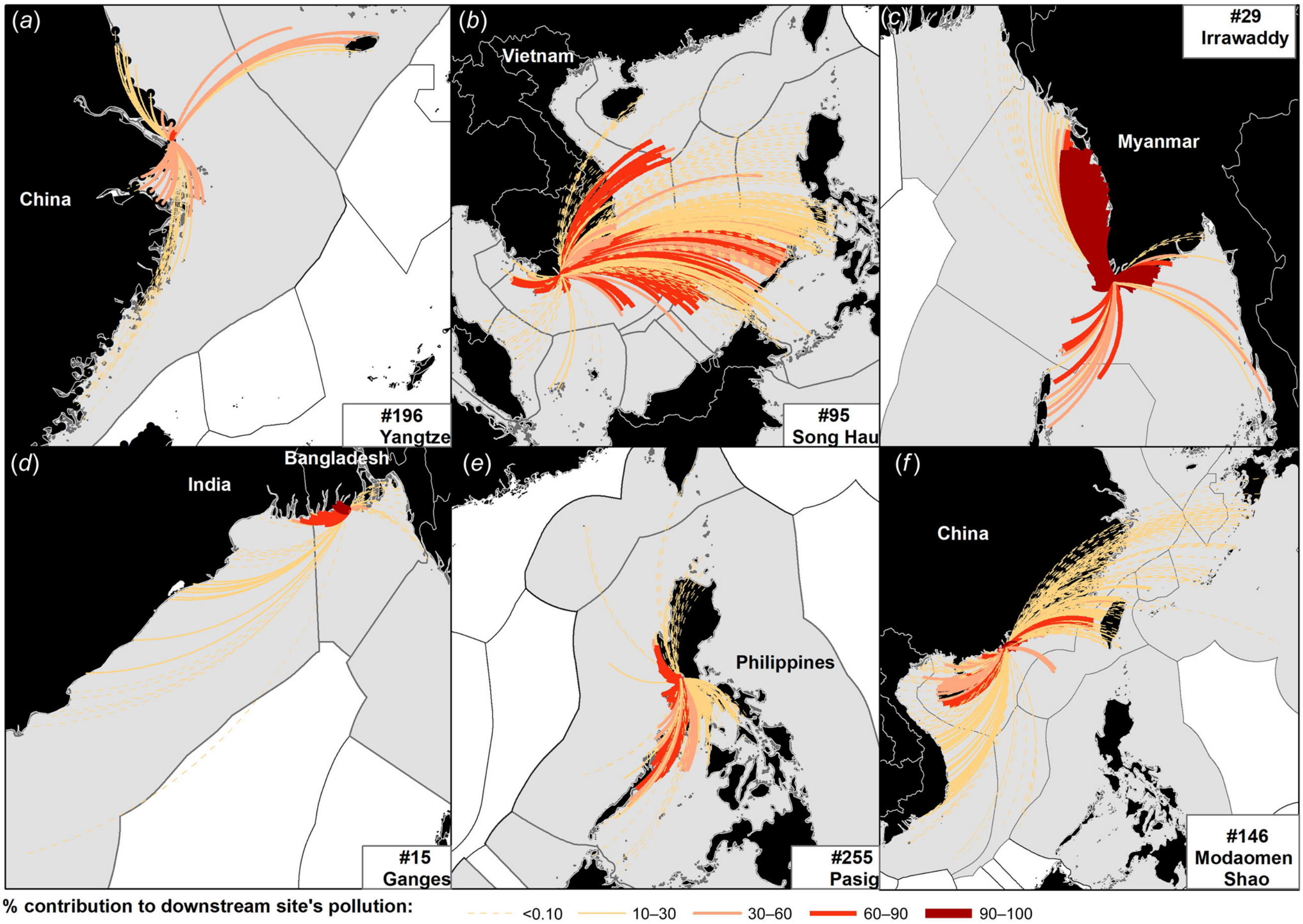

Fig. 5. The six rivers that are important for multiple objectives are shown in panels (*a*)–(*f*). The Exclusive Economic Zones affected by their downstream pollution are in grey. The percent contribution of the total inflow of plastic debris to individual downstream receiving sites can be used to identify how the benefits are distributed across different jurisdictions.

Highlighting trade-offs with a consequence table

The most promising source rivers for management can be compared across all metrics in parallel to understand the trade-offs for all objectives and type of impact (Table 2). A detailed investigation across all metrics for the six candidate rivers suggests there is no clear best or worst option and therefore requiring managers to make trade-offs based on what they consider most important. The Yangtze River carries by far the greatest volume of debris and contributes the largest volume of debris into downstream sites. If reduced at this source, it could cut downstream pollution to all key biodiversity areas by 18% and the general coastline by 15%, yet other source rivers would be better at reducing impacts on coastal populations or coral reefs. The area and number of sites that benefit is also substantially smaller than the area that would benefit from other clean-up options. A clean-up intervention at the Ganges in India could reduce pollution into Marine Protected Areas by 16% (the single best benefit to MPAs) and into Key Biodiversity Areas by 8%. Meanwhile, River Song Hau in Vietnam would be the best option to benefit the highest number of sites (412) and the largest area overall, and also strongly benefits populations. However, these benefits are distributed over 10 nations, which might reduce the motivation of the Vietnamese government to invest in clean-up. In addition, the total volume at this source is relatively small compared to the other top-five rivers. Finally, the Pasig River and Modaomen Shao Channel rank second across multiple social and environmental objectives, as well as general statistics, however, with reduced technical challenges that are expected in the enormous estuaries of the Yangtze River and the River Ganges.

Rivers that are targeted through the Clean Currents Coalition (https://cleancurrentscoalition.org/coalition-projects) include the Assi River (Bangladesh: #9–18), the Song Hong River (Vietnam: #119–127), the Lat Phrao Canal (Thailand: #77–80), and the Citharum River (Indonesia: #441–442). The Assi River is a tributary to the Ganges, which appears in a high rank for all objectives except for coral reefs. However, due to the variability in debris load across the wide delta, it might be a challenging location to create targeted impacts for downstream sites.

Table 2. Consequence table comparing the top six rivers (columns) and all impact metrics (rows).

	Metric	Habitat type	15 River Ganges (India/Bangladesh)	29 Irrawaddy River (Myanmar)	95 River Song Hau (Vietnam)	146 Modaomen Shao Channel (China)	196 Yangtze River (China)	255 Pasig River (Philippines)
General impact statistics	Eqn 4: Impact at source river (t)		35,420	31,242	16,893	59,003	82,921	25,992
	Eqn 3: downstream impact across all sites (t)		1765	1460	527	2945	5508	1731
	Fraction of the river load that pollutes sites across system (%)		5	5	3	5	7	7
	# sites impacted by this source		69	110	412	396	95	238
	Area impacted (across all sites) (km^2)		32,768	31,104	213,056	163,200	38,656	113,344
	# sites this source is the main source of pollution		18	75	175	82	35	106
Impact for environmental objectives	Eqn 2: volumetric impact downstream (t)	Reef	<1	232	150	408	2	533
		KBA	1023	507	52	291	2331	287
		MPA	1138	227	121	508	634	368
		Coast	1443	1401	448	2791	4444	1695
	(%) Reduction in pollution across sites and area	Reef	<1	8	5	14	<1	18
		KBA	8	4	<1	2	18	2
		MPA	16	3	2	4	9	5
		Coast	5	5	2	9	15	6
	# sites with reduced pollution	Reef	2	45	232	103	6	120
		KBA	35	22	35	96	34	27
		MPA	21	8	82	106	23	39
		Coast	65	87	277	333	79	206
	(km^2) Area with reduced pollution	Reef	256	5039	46,076	22,237	668	35,018
		KBA	5970	3391	29,555	33,785	4309	27,624
		MPA	7113	5013	53,262	27,767	5673	28,032
		Coast	19,441	22,643	92,753	97,204	25,181	53,980
Impact for social objectives	Impact on # of people within 8 km^2 vicinity		1,677,428	335,997	3,455,702	7,615,236	1,671,724	1,970,634
	Main source of pollution for # of people within 8 km^2 vicinity		421,905	155,384	673,479	2,213,270	654,750	846,403
Feasibility	Technical feasibility	Only used for preselection based on downstream sites with highest pollution						
	Political feasibility: # EEZ impacted		3	3	10	9	2	3

KBA, key biodiversity area; MPA, marine protected area.

Detailed benefit analysis for six potential high-impact rivers identified in Table S3 and Fig. 4. The consequences and trade-offs are clearly identified in this quantitative information on plastic debris pollution at the source and downstream sites for all different environmental and social objectives.

Dark blue, best options for each metric; mid blue, second best options for each metric, light blue third best option for each metric. Technical feasibility is greyed out as it was used during preselection of most promising options.

Variability of ranks across different model parameters

We assessed the variability in the first 100 ranks based on rivers with high flows to a receiving site (*volumetric impact*, Eqn 2), rivers contributing high fractions of the inflowing plastic pollution at a receiving site (*relative impact*, Eqn 1) and rivers causing high inflow of plastic debris across all receiving sites (*total downstream impact*, Eqn 3) across six 'sensitivity' scenarios (shallow and deep currents, high and low settlement rate, mean and high estimates for modelled load of debris in rivers). Ranks based on the *volumetric impact* were stable across the first 100 ranks (Eqn 2, Supplementary Material S5 top). Most rivers appeared in the first 100 ranks in all scenarios and had low or no variability in these ranks. All six rivers appeared in the top ranks. Variability among ranks based on the *relative impact* (Eqn 1, Supplementary Material S5 middle) was higher, many rivers appeared only in some of the scenarios in the first 100 ranks, and only one of the rivers we examined appeared in the first 100 ranks. Variability among the first 100 ranks for the *total downstream impact* (Eqn 3, Supplementary Material S5 bottom) was highest, with most rivers only ranking in the first 100 ranks in few of the scenarios, and none of the selected rivers appeared in these top ranks. The results suggest that planning based on the flow of volume from source rivers to receiving sites might be the most robust metric when considering a range of likely parameters in the model.

Discussion

An important aspect of the SDM process is the well-defined metrics that show the nuances of different objectives with a clear and transparent method to navigate the trade-offs between them. As expected, prioritizing different objectives and metrics lead to different priority source sites for management. We found three main types of trade-offs for marine debris management in south-east Asia: (1) reducing total plastic vs reducing impact at specific downstream sites; (2) reducing the downstream impact on social vs environmental outcomes; and (3) reducing impact *per se* vs the feasibility (political and technical) of implementation. Each of these main trade-offs are described further, below.

The first trade-off is between reducing the volume of circulating debris in the open ocean vs reducing negative impacts in specific places of value. Within our model, approximately 5% of virtual plastic settles in destination habitat after 2 months, roughly matching estimates from previous studies, considering that only 1% of marine plastic debris is believed to be bound in surface waters (Eunomia Research & Consulting Ltd 2016). Therefore, targeting clean-up at locations carrying a high load to reduce the accumulation of large volumes of pelagic pollution seems to be a reasonable strategy. However, there are trade-offs with the downstream site-specific priorities. Several rivers that carry the highest volumes of pollution do not rank high for many other places or habitats of value. When the aim is to reduce the overall volume of marine debris and plastic pollution in general, regulating production in general seems to be a more feasible approach than trying to intercept large volumes along their trajectories after they enter the environment, as there is a direct correlation between production of plastic and plastic pollution (Cowger *et al.* 2024). Improvement of waste management infrastructure has emerged as a priority in national policies in the seascape, confirming the risk of repeated leakage of retrieved debris (Arifin *et al.* 2023). Indeed, the rivers we assessed in detail due to their large benefits for multiple objectives were located in China, Vietnam, and the Philippines, which ranked along with Indonesia as countries with the most mismanaged waste material (Jambeck *et al.* 2015). This introduces the risk that removal of debris is only temporary. At the same time, some rivers that are the main sources of pollution for specific sites or coastal populations are not necessarily among the rivers with the highest load in general, but management of these sites would have additional benefits that go beyond the amount of removed debris.

The second key type of trade-off is between reducing the impact across competing values (e.g. social vs environmental) at downstream sites. A clean-up intervention at River Song Hau would provide some of the greatest benefits to the coastal population as well as the numbers and area of downstream sites, especially coral reefs and marine protected areas (MPAs). However, this option provides much lower benefits for more ecologically meaningful metrics such site-specific plastic inflow (volume or percent) than a clean-up at the Irrawaddy River, Modaomen Shao Channel or Pasig River. A clean-up at the River Ganges would provide the best ecological meaningful benefits to MPAs and key biodiversity areas (KBAs) but some of the lowest benefits to reefs and human populations. A clean-up at the Pasig River would provide the highest reduction of percent and volume of plastic debris inflow to coral reefs, but at the same time, provide some of the lowest benefits to KBAs and marine protected areas among the assessed options. Despite the necessity for decision makers to navigate the trade-offs between competing objectives, the transparent and quantitative comparison of consequences makes this decision-making process clear and equitable, enabling a strategic investment into the most appropriate location and action.

The third general trade-off is between the best outcome across all or most objectives regarding downstream benefits vs the most feasible implementation (least political and technical challenges). Two rivers (Ganges and Yangtze) with the highest volume of debris would be clear priorities, yet provide lower benefits to coastal populations or coral reefs than several other options. These two rivers would also be technically challenging due to their wide estuaries stretching over hundreds of kilometres. However, they should also be politically feasible and tractable as the pollution destinations from these top sources are largely contained within their own Exclusive Economic Zone. In contrast, the source River Song Hau (Vietnam) or Modaomen Shao Channel (China) contribute plastic pollution to many downstream nations, making the source-destination impact management less politically feasible and motivating. Collaborations that account for these types of burden sharing of costs at the source relative to the downstream benefits will be key to achieving impacts on a meaningful ecological scale, as is the case regarding other cross-jurisdictional ecological challenges (Clark *et al.* 2023).

Implications of our study for identified priorities in the management of marine plastic debris in the Asian seascape

Movement patterns, dispersal pathways, and accumulation zones, as well as their variability, are highlighted as a current important knowledge gap and priority areas of research for marine plastic pollution in Asia (Omeyer *et al.* 2022). The urgent need to quantify expected impacts on several marine habitats and coastal populations, which could serve as a proxy for ecosystem services and degradation of seafood safety, is identified as another key area of research. Our study does not only provide workable examples and analysis pathways for the identified priorities, we also showcase how a rigorous framework can be applied to identify intervention locations with high impact for a combination of objectives, including the consideration of the geopolitical role of countries. In the following, we put our study in context of several countries.

For example, Indonesia experiences increasing environmental pressures and costs of marine plastic debris in the Coral Triangle and is one of the first nations to have a National Action Plan on marine plastic pollution. However, there seem to be no clear priorities or set processes for the selection of clean-up locations yet, and only few studies have investigated sources and trajectories of marine debris pollution that arrives in its jurisdiction (Purba *et al.* 2019).

Several rivers in Indonesia have been among the top source rivers of marine plastic debris in different studies (Lebreton *et al.* 2017; Meijer *et al.* 2021), and population and consumption growth, as well as severe problems with waste management, predict a worsening of plastic pollution in the future (Lestari and Trihadiningrum 2019). Published modelling for Jakarta suggests outgoing debris floats into the Indian Ocean, while incoming debris comes from Java, Sumatra, Kalimantan, and the Gulf of Thailand (Iskandar *et al.* 2021). In our study, several rivers in Indonesia ranked as high priorities for two objectives (contribution to site pollution and pollution that impacts people).

In Vietnam, only 10–15% of plastic waste gets recycled, with a generation of 3.7 million tonnes of plastic annually (Veettil *et al.* 2023). The government is dedicated to reducing the inflow of debris into the sea by 75% by 2030 and banning single-use plastics. The national strategy on marine debris management lists the monitoring and assessment of important sources of marine plastic debris as a key objective (VASI (Vietnam Administration of Seas and Islands) 2020). The River Song Hau in Vietnam emerges as one of the most impactful intervention locations for the largest number of sites and overall area that could benefit from a reduced inflow of plastic debris in our study. Other studies mention mangroves and seagrasses as important sinks of plastic debris. These additional habitat types could be integrated in the same way as the reefs, MPAs and KBAs in our analysis, which might identify additional rivers as a priority for clean-up actions than the ones we identified here (Harris *et al.* 2021; Veettil *et al.* 2023). We only have included area of extent as a parameter in our analysis, but habitat quality (e.g. based on environmental criteria) is often a key factor in prioritisation process for conservation. If information on the relative quality of habitats exists, it can be easily added as a relative weighting factor.

In the absence of national monitoring data, the national waste management in the Philippines is based on international estimates (Alindayu *et al.* 2023). Our results indicate that the management of inflow to coral reefs can be managed to a high degree by national actions; for example, intercepting pollution at the river mouth of the Pasig River, which could at the same time contribute to the collection of local data (Alindayu *et al.* 2023). Manila Bay was identified as the location with the highest accumulation of debris in a recent sampling effort, confirming the modelled hotspot (Gomez *et al.* 2023).

Thailand relies on mainly voluntary measures, which currently fail to mitigate the growing problems of plastic waste, and the country is not set up to provide commercial plastic recycling facilities (Marks *et al.* 2020). Transboundary partnerships are key to enabling effective policies and strategic action on the growing plastic waste problem (Marks *et al.* 2020). Our study showed clearly that not every clean-up intervention at a river with a high pollution load would provide the same direct short-term reduction of debris inflow at downstream sites of value. Learning how to assess direct benefits for different objectives could be an additional motivation for countries to invest in interception technologies at the source and inform international collaboration. Even though we did not explore a particular river from Indonesia or Thailand in full detail, the data and methods provided would make it easy to assess all options in the same way.

Improvements in the decision-making process for selecting clean-up sites

Compared to other methods that offer guidance during multi-objective prioritisation procedures for conservation management, such as portfolio theory (Beyer *et al.* 2018) or Pareto Ranking (Chollett *et al.* 2022), SDM has the advantage that it instructs decision-makers to investigate the information behind calculated ranks. A critical aspect in the context of mitigation options for marine plastic debris pollution is that SDM encourages decision makers to spend time developing a clear scope of the problem and relevant objectives and metrics. Exploring and defining different values and objectives produces relevant information about the different types of impact a clean-up effort can have beyond the removed volume of debris. This process helps to understand that multiple quantitative metrics are needed to fully understand the breadth of potential impacts and the related trade-offs for different clean-up locations. The importance of considering multiple metrics instead of single indicators to capture the different dimensions of the ecological context has been stated in other conservation contexts (Adams *et al.* 2021; Wyborn and Evans 2021).

The results of our case study highlight for the first time how important deliberation on different values, objectives and metrics is in the context of marine plastic debris by showing that the choice of different performance measures leads to a different ranking of clean-up locations. Our case study provides clear concepts for decision makers and planners to expand the current predominant focus on removing large volumes of debris by adding considerations on direct benefits to species and habitats downstream. As most species and ecosystems suffer from multiple impacts, reducing plastic pollution might bolster their ability to withstand other threats (Côté *et al.* 2016).

Constraints and uncertainty

Our study has several constraints for informing site selection for debris management. For informing real world management, additional analysis would be needed to explore a number of uncertainties, particularly model uncertainty and input parameter uncertainty (Regan *et al.* 2002; Rounsevell *et al.* 2021). The three main caveats in our analysis are model resolution, the physics of plastic dispersion in the water column, and plastic debris volumes at the sources.

The choice of data describing the ocean currents influences results because they are the driving force behind measuring trajectories. The first constraint of the HYCOM model is its resolution of 10 km^2, which limits detail for the passages between islands throughout the Coral Triangle and does not account for tidal forcing or other small-scale aspects of ocean currents. Reruns with alternative current data in higher resolution would be required to quantify variation in results based on the choice of current data and might also provide better information on the differences we found in trajectories coming from different locations within the estuaries of the Yangtze River and the River Ganges. Particularly for coastal zones, additional exploration of the impact of resuspension rates at beaches and other shallow coastal zones would be needed to explore the robustness of the results.

The second constraint of our model regarding the physics of plastic dispersion includes the considered parameters for movement. While our model includes advection and dispersion, we have not accounted for windage, sinking, settling, beaching, refloating or biofouling and degradation that might change physical properties like size and shape over time, which in turn affect drift behaviour (Chubarenko *et al.* 2016; Khatmullina and Chubarenko 2019; van Sebille *et al.* 2020).

The third constraint is the reliance on one dataset on debris load in rivers. We could have tested alternative data sets, as done in other studies investigating the settlement of plastic debris (Meijer *et al.* 2021). Because we wanted to focus our study on the concept, it seemed more appropriate to include a general approach to investigating the robustness of results than adding detailed sensitivity and scenario testing of the chosen models and parameters that have been addressed elsewhere (Simons *et al.* 2013; Treml *et al.* 2015; Jones *et al.* 2016; Schlaefer *et al.* 2022).

Costs are a key factor in decision making, however, they differ across different countries based on currency, costs of materials, salary costs and the size and type of intervention that is chosen for intercepting debris (Silva *et al.* 2021). Willingness to pay studies are one example of already existing data on environmental costs in the region (Suryawan and Lee 2024; Suryawan *et al.* 2024*a*, 2024*b*). Alternatively, expert elicitation could provide an avenue to produce and use cost related data in a real-world application. Costs, as well as estimates for effectiveness of different interception technologies, can be added to the consequence table as a row but should be transferred into a comparable unit, for example purchasing power parity. For transparency, all impact metrics should be reported in real-world quantitative units (e.g. tonnes, km^2) in order to be comparable across all alternative site locations.

The utility of prioritising locations for local clean-ups in a global context

Removing plastic debris that has already entered circulation pathways is a temporary and local mitigation strategy and is not comparable to a long-term strategy based on policies and regulations that can reduce the overall inflow into the environment (Bergmann *et al.* 2023; Cowger *et al.* 2024). Considering the socio-economic realities of increasing production and high rates of waste mismanagement, the production of new plastics needs to be reduced and regulated dramatically (Diana *et al.* 2022*a*; Stoett 2022). This is particularly important in countries with high waste exports, such as Japan, the United States or the Netherlands (Basel Action Network 2021). As the problem of pollution is linked to the mismanagement of waste, trade flows are an important aspect of the problem. A contentious report focusing on Asian countries was retracted because the aspect of international trade and hence the actual polluters were not reflected in the methods used, creating a misleading narrative (The Guardian 2022). Illegal trade (Interpol 2020) to countries with high rates of mismanaged waste, such as an estimated 70% for

Thailand (Marks *et al.* 2020), creates doubts that salvaged volumes of debris will not enter the environment again.

An international movement to create a legally binding treaty to end plastic pollution by 2024, along with waste management and regulation, have been highlighted as an important avenue for change in impacted countries such as the Philippines, Indonesia, Malaysia, or China (Eisma-Osorio 2021; Yin 2021; Kamaruddin *et al.* 2022; UNEP 2022*a*). However, negotiations among countries on the exact details of the treaty are slow and influenced by industry (Diana *et al.* 2022*a*, 2022*b*; CIEL 2024). Despite the initiative, the production, use and disposal of conventional fossil fuel-based plastics are increasing and are forecast to grow to 19% of the global carbon budget until 2040 (Law *et al.* 2020; UNEP 2022*b*; Lee and Volvovici 2024). The growing production and waste streams drastically reduce the expected effectiveness of clean-ups, and the impacts on human health and the environment can be substantial (Human Rights Watch 2022).

Conclusions

Without more fundamental regulatory measures, any local management focusing on the clean-up of marine debris is likely to be dwarfed by the predicted growing inflow of mismanaged plastic waste into aquatic and terrestrial systems. However, as long as plastic debris from waste streams is likely to enter the environment, intercepting trajectories to downstream sites with high social or environmental value gains more weight than just removing high volumes, as removal is likely to be only temporary.

Our study highlights how SDM could be used to identify and navigate key trade-offs in the mitigation of multiple impacts of marine plastic debris. The insight into the variability of the most important social, technical, political, and environmental consequences of each possible intervention site demands rigorous thinking but also offers transparent and logical prioritisation. While it is unlikely to identify a clear 'best' river to mitigate pollution, the use of SDM guides decision-makers to identify meaningful metrics that reflect their values and provides a robust and intuitive process to understand the consequences of any site selection compared with the alternatives.

There are several important aspects to consider before our framework would be fit for application:

1. All important and interested stakeholders in the planning region should be invited or consulted. Our study provides some suggestions, but each planning context requires revisiting who should be invited and consulted during the scoping and planning.
2. Similarly, the set of important objectives and metrics to consider would need to be confirmed or updated based on the relevant socio-ecological context and specific values of the involved stakeholders. For example, metrics could be added or modified with local information on the relevance to their management goals, such as including the social value of small fishing villages that provide food to the region.
3. Data and models used in the analysis should reflect the most up-to-date options and best practices for the purpose. For example, since the time of our analysis, more accurate estimates of plastic debris in rivers have become available for the Asian seascape, and field-based observational data should always be considered where appropriate to produce more accurate estimates for pollution flows and impact on biodiversity (van Emmerik *et al.* 2019; Owens and Kamil 2020; Seo and Park 2020; Fauziah *et al.* 2021; Meijer *et al.* 2021; Iskandar *et al.* 2022; Roman *et al.* 2022). The hydrodynamic model to simulate plastic transport should reflect the seascape as accurately as possible, and ensembles could improve accuracy of predicted pathways and uncertainty.
4. The sensitivity analysis to explore uncertainty in the results should be based on the priorities of decision makers and the used data and models.
5. In summary, while our study should provide a clear conceptual framework and highlight likely regional priority areas for intervention, implementation will likely happen on the regional or national level, and revisiting and adjusting each step with the most relevant content for the specific socio-political and environmental context is highly advisable.

Supplementary material

Supplementary material is available online.

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Data availability. Data and code used to produce results are available on figshare (https://doi.org/10.6084/m9.figshare.26491714.v1).

Conflicts of interest. The authors declare that they have no conflicts of interest.

Declaration of funding. This study was conducted as part of a PhD at the University of Melbourne and was funded through the Australian Research Training Program Scholarship.

Acknowledgements. We thank Dianne McLean, Kay Critchell, Maria Beger, and Iliana Colette for valuable feedback on the manuscript. We also thank Win Cowgar from the University of California, Molly Morse from the Benioff Ocean Initiative, and Erika Scelfo from TerraCycle for the helpful engagement in the early stages of our study. This research was supported by the University of Melbourne's Research Computing Services, Spartan HPC, and the Petascale Campus Initiative.

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