Threat maps for conservation planning and policy across spatial scales

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Abstract

Reducing threats to species will play a central role in implementing the Kunming-Montreal Global Biodiversity Framework. This makes it critical to understand the state of knowledge on where human activities directly threaten species and how such knowledge can inform conservation planning and policy decisions. The term 'threat mapping' has been applied to maps of threatened species (species status), human activities irrespective of species presence (pressures), or maps of the spatial co-occurrence between species and human pressures (threats). Inconsistency in terminology is one of multiple factors that hampers the ability of threat maps in guiding effective conservation actions. Here, the terminology is refined to define a threat map as a geographic representation of the spatial co-occurrence between species and threatening human pressures. The availability, characteristics, and utility of these maps has not yet been discussed or formally reviewed, yet it has the greatest potential to inform threat abatement activities. Therefore, this thesis aims to overcome barriers hindering the uptake of threat maps into threat abatement planning and policy decisions by: increasing the accessibility of existing threat mapping applications, increasing awareness of the gaps and biases in threat map production, and investigating the use of research practices that enhance relevance to decision-makers. This thesis revealed a rapidly increasing body of literature that was unevenly distributed across all collected attributes, mismatches in research effort relative to a quantitative indicator of conservation need, intended pathways to action that are focused on intermediary conservation planning processes rather than specific actions, and some stakeholder engagement in the design and delivery of studies. The findings provide a set of valuable resources that can be used in the design of future threat mapping research as well as highlighting eight high-priority gaps. Filling these gaps will have invaluable benefits to the achieving goals on reducing threats and preventing species extinctions.

Collaborations

The following people made contributions to this thesis.

Philip McGowan and Louise Mair provided expert advice that helped to refine the protocol for the systematic map of the literature (chapter 2) and provided comment on the draft that was subsequently published in the journal Evidence.

Philip McGowan, Louise Mair, and Andrew Suggitt provided expert advice that aided the implementation of the systematic map of the literature. Emily Hickinbotham screened and coded 20% of all studies at each stage for the systematic map of the literature (chapter 3). Mark Shirley and Roy Sanderson helped to launch the interactive database of studies (chapter 3). Philip McGowan, Louise Mair, Andrew Suggitt and Emily Hickinbotham provided comments on the draft of chapter 3 that was subsequently published in the journal Environmental Evidence.

Ben Rowland helped to screen the statements of stakeholder involvement (chapter 5).

Steve Rushton provided advice on modelling approaches for and commented on drafts of chapter 4.

All data collection and analyses were performed by Francesca Ridley under the guidance of Philip McGowan, Louise Mair and Andrew Suggitt. All text was written by Francesca Ridley and drafts of each chapter were read and commented on by Philip McGowan, Louise Mair and Andrew Suggitt.

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Chapter 1: Introduction

1.1. Background

1.1.1. The biodiversity crisis

Rates of species extinctions due to human activities far exceed the expected background rate (Pimm *et al.*, 2014). Over 30,000 animal and plant species are assessed as threatened with extinction or extinct in the wild, of which the populations of over 19,000 are decreasing (IUCN Red List, 2022). Considering that approximately 92% of described animal and plant species have not yet been assessed and ~20,000 are classed as Data Deficient (IUCN Red List, 2022), it is estimated that 1 million species face extinction (IPBES, 2019a).

As a component of biodiversity, species contribute vital services to humanity. These services include regulating essential environmental conditions (e.g. water, air, and soil quality), provision of material benefits (e.g. food, medicines, and energy), and non-material or cultural benefits (e.g. psychological health and spirituality, Díaz *et al.*, 2015; IPBES 2019a). Maintaining a diversity of species also maintains a diversity of current and potential future services, facilitating the capacity to adapt to changes and new challenges (Mace, Norris and Fitter, 2012).

The Convention on Biological Diversity (CBD) entered into force in 1993 with three objectives: the conservation of biological diversity, the sustainable use of natural resources, and the fair and equitable sharing of nature's benefits (CBD, 2006). However, successfully achieving these objectives has proved a challenge. None of the Convention on Biological Diversity's (CBD) twenty Aichi targets were fully met by 2020 and only seven were partially met (CBD, 2020a). The adoption of the Kunming-Montreal Global Biodiversity Framework presents the opportunity to revive momentum in addressing this global challenge and achieve the transformative change required to bend the curve of biodiversity loss (Leclere *et al.*, 2020; CBD, 2022a).

Knowledge on where and how human activities directly threaten wild species can enable the conservation of biological diversity and identify where the use of natural resources can be done more sustainably. However, such processes are geographically and conceptually entangled with the benefits that humans derive from nature, on which wellbeing and livelihoods often depend. To achieve the convention's vision of 'Living in Harmony with nature', decision-makers must combine evidence on threats to species with knowledge on human needs to design strategies that maintain essential services to people while reducing and mitigating the threats to biodiversity

1.1.2. Threats and threat mapping

Rather than take conservation action on a species-by-species basis, if conservation action is targeted at addressing threats, multiple species and ecosystems may benefit from individual actions. Eighty percent of threatened and near-threatened species are affected by at least one threat (Maxwell *et al.*, 2016) and threatened island species are impacted by 2.6 threats on average (Leclere *et al.*, 2018). Overall the most frequently-reported threat in IUCN Red List Assessments is direct exploitation (e.g. hunting, fishing, and wild plant collection), followed by agricultural activity and urban development (Maxwell *et al.*, 2016). Furthermore, a synthesis of 575 studies of driver impacts found that land/sea-use change was the strongest driver of biodiversity loss and the additional importance of other drivers (e.g. direct exploitation, climate change, and pollution) varied depending on the biodiversity indicator being considered (e.g. species populations, community composition, ecosystem function, Jaureguiberry *et al.*, 2022). It is evident from such analyses that the threats to species are widespread and affect geographies, taxonomic groups and ecological realms (i.e marine, terrestrial, and freshwater) differently (Halpern *et al.*, 2007; Cazzolla Gatti, 2016; Schulze *et al.*, 2018; Bellard, Marino and Courchamp, 2022; Jaureguiberry *et al.*, 2022).

The abatement of threats to species will be central to the implementation of the Kunming-Montreal Global Biodiversity Framework. Among other things, under Goals A and B human-induced extinctions should be halted, extinction risk reduced, and biodiversity should be sustainably used and managed by 2050. To achieve these, eight of the action-orientated targets seek to reduce threats and a further two seek to sustainably manage the use of natural resources, by 2030 (CBD, 2022a, Table 1.1). Target 21 also reinforces the importance of ensuring the best-available data is accessible to relevant decision-makers (CBD, 2022a, Table 1.1). Therefore, in order to meet the ambitious vision of 'Living in Harmony with Nature by 2050', there is an urgent need to consolidate and evaluate the available evidence on where human activities currently impact species and increase its accessibility to decision-makers.

Table 1.1. Action targets of the Kunming Montreal Global Biodiversity Framework (KMGBF) that are relevant to this thesis and threat mapping. Summaries are adapted from the KMGBF text (CBD, 2022a).

Target group	Target	Summary
1 - Reducing Threats to Biodiversity	1	All areas under participatory, integrated and biodiversity-inclusive spatial planning to bring the loss of areas of high biodiversity importance close to zero.
	2	30% of degraded terrestrial, inland water, coastal, and marine areas are restored.
	3	30% of terrestrial, inland water, coastal, and marine areas are effectively conserved and managed.
	4	Urgent management actions to halt human-induced extinction of known threatened species and significantly reduce extinction risk.
	5	Use, harvesting and trade of wild species is sustainable, safe and legal, minimizing impacts on non-target species and reducing risk of pathogen spill over.
	6	Eliminate, minimize, reduce, and or mitigate the impacts of invasive alien species.
	7	Reduce pollution risks and the negative impact of pollution from all sources.
	8	Minimize the impact of climate change and ocean acidification on biodiversity and increase its resilience through mitigation adaptation and disaster risk reduction.
2 - Meeting people's needs through sustainable use and benefits sharing	9	Management and use of wild species is sustainable.
	10	Ensure that areas under agriculture aquaculture, fisheries and forestry are managed sustainably.
3 – Tools and solutions for implementation and mainstreaming	21	Ensure that the best available data, information and knowledge are accessible to decision makers, practitioners and the public.

Over recent decades there have been many attempts to define and classify the processes driving species extinctions (Battisti *et al.*, 2016). Attempts to classify these processes agree that, ultimately driven by complex social, economic or ecological factors, human activities or human-initiated processes (threat/pressure/source) impact a biological entity (e.g. populations, communities, or ecosystems) via the alteration of ecological attributes (stressor/mechanism, Salafsky *et al.*, 2008; Balmford *et al.*, 2009; IPBES, 2019b; Williams, Balmford and Wilcove, 2020). Disagreement has arisen around the specific terminology used and what processes belong where in each framework. For example, IUCN Red List assessments apply the hierarchical framework of (Salafsky *et al.*, 2008) in which, among others, agriculture, alien invasive species, pollution, and climate change are all considered to be direct threats. Whereas, Balmford *et al.* (2009) consider climate change to be a threat source, and alien invasive species, pollution and land-use change to be threat mechanisms. Further, the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) considers all factors that drive change in natural systems to be either direct or indirect drivers (direct drivers being synonymous with threats/pressures/sources, IPBES, 2019b). According to the IPBES typology of direct drivers, the conversion of land to uses such as agriculture or residential development are all collectively considered land-use change, and any resulting contamination of air, water, or soil is classed as pollution (both are direct drivers, IPBES, 2019b).

Which framework may be appropriate depends on the application and context. The IPBES five direct drivers of biodiversity loss (IPBES, 2019b) offers a simplicity that is useful for communicating with policy. Balmford *et al.* (2009) is better suited to applications intending to capture interactions among some threatening human activities and processes. Salafsky *et al.* (2008), as a hierarchy of 99 individual sub-classes among 12 higher-classes, offers a comprehensive collection of known threats. Therefore, the utility of each depend on the context in which they are being applied.

As the purpose of this investigation is to systematically consolidate available information, the comprehensive definition of Salafsky *et al.* (2008) was applied. As such, threats are the human activities (e.g agriculture, residential development, direct exploitation) and direct human-initiated processes (e.g. climate change, invasive species, pollution) that impact wild species.

The threat mapping literature also suffers from similar inconsistencies in coverage and defining terminology. The terms threat, pressure, impact, or risk mapping have been used somewhat interchangeably to refer to any spatial representation of species threat (e.g. extinction risk) or threats to species. Maps range from independently representing either threatened species (Orme *et al.*, 2005; Brooks *et al.*, 2006) or threatening human-activities irrespective of species presence (Sanderson *et al.*, 2002; Venter *et al.*, 2016a), through threatening human activities restricted to where species are, or are likely to be (Halpern et al., 2008; Geldmann, Joppa and Burgess, 2014; Allan et al., 2019), to maps that measure the strength of interactions between species and threats (i.e impact, Di Marco *et al.*, 2018; Harfoot *et al.*, 2021, Fig 1.1). Some defining frameworks restrict the definition to one of these map types (TNC, 2012) and others use threat mapping as an all-encompassing term (Tulloch *et al.*, 2015; Ostwald *et al.*, 2021).

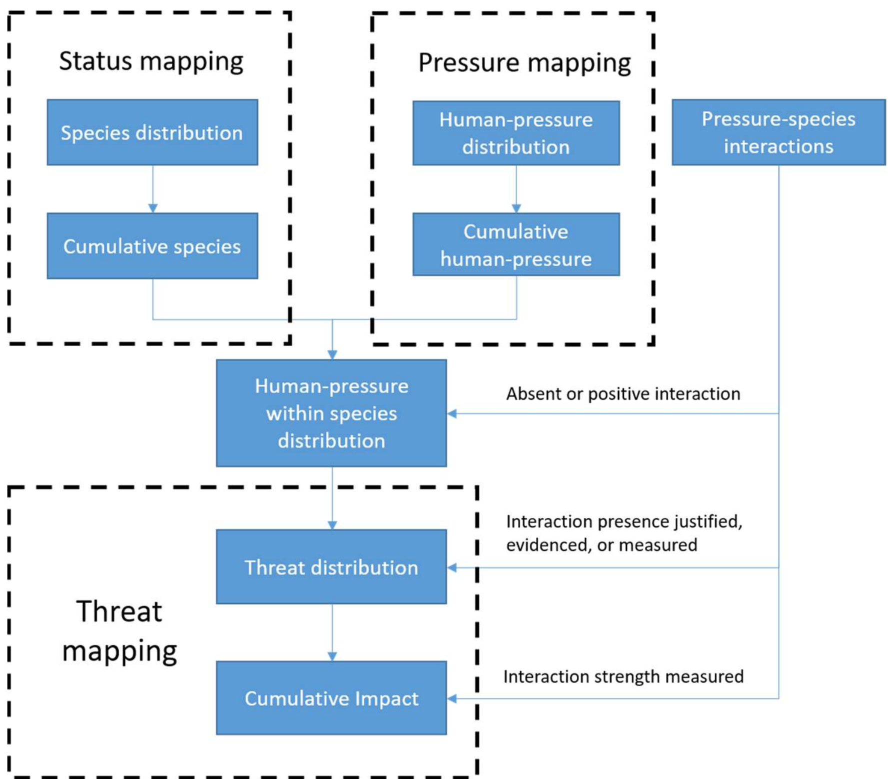

Figure 1.1. A typology of threat mapping methodologies. Adapted from Ostwald et al (2021).

Threat maps have a variety of purposes in conservation practice and policy that are closely linked to map characteristics such as complexity and scale. The utility of global-scale and multi-national threat maps (e.g. Fig 1.2a) in directing large scale financial and political support to particularly priority regions has been demonstrated (Myers *et al.*, 2000; Brooks *et al.*, 2006; Tulloch et al., 2015; CEPF, 2020). In contrast, local-scale maps (e.g. Fig 1.2b) are often combined with multi-criteria decision making or cost-effective analyses to plan fine-scale interventions and prioritise limited resources (Margules and Pressey, 2000; Bertolino *et al.*, 2020; Tulloch et al., 2020). Of the types of maps described, the resulting priorities are shown to get more refined the more data is added (e.g. on species distributions, threats, and interactions, Ostwald *et al.*, 2021). More complex maps are expected to have greater ability to inform conservation decisions than hotpots of species or pressures alone (Tulloch et al., 2015). Reducing and mitigating threats to species can only be effectively achieved through knowledge on where threatening human activities directly interact with wild species.

a b

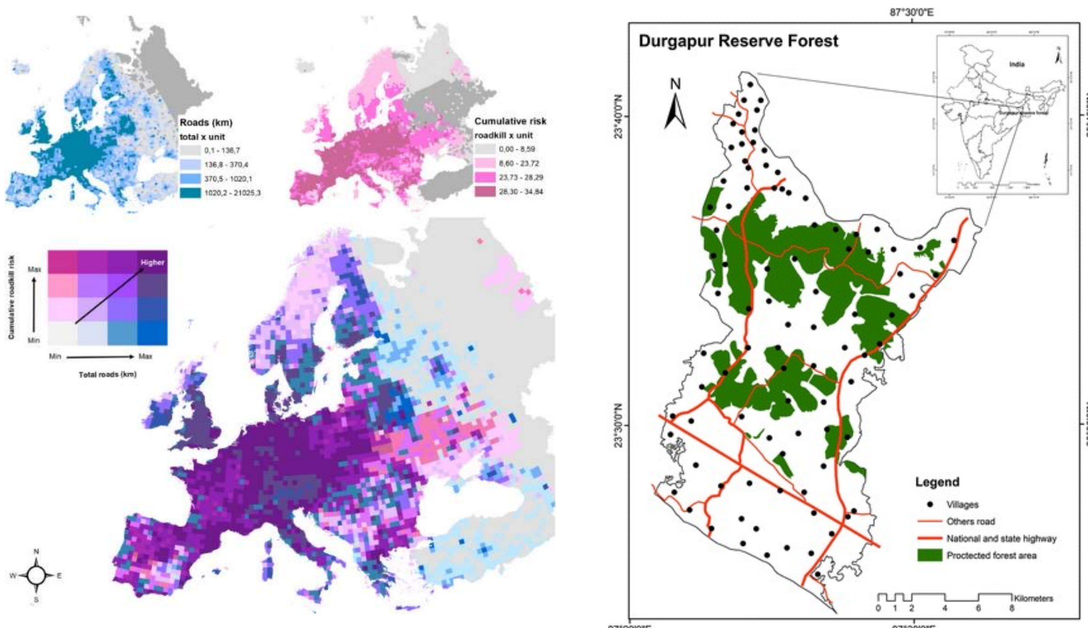

Figure 1.2. Examples of threat maps using different methods at different spatial scales a) avian roadkill-risk across Europe from Morelli et al. (2020) and b) fragmentation of a protected forest due to road infrastructure and settlements in West Bengal, India (Dutta et al., 2017).

1.1.3. Threat-mapping research to decision-making

Despite the purpose of conservation science being deeply rooted in its ability to inform actions (Soulé and Wilcox, 1980; Whitten, Holmes and MacKinnon, 2001), the effective translation of science into decisions requires active engagement (Sutherland *et al.*, 2020a; Ferreira and Klütsch, 2021). This has been long understood. It is 20 years since Cash *et al.* (2002) published their 'Salience, Credibility, Legitimacy' framework for linking science to decision-making, and Sutherland *et al.* (2004) found that primary scientific literature was the least utilised source of information for a sample of conservation practitioners. Since then, there has been a paradigm shift towards multi-directional knowledge exchange (Best and Holmes, 2010; Fazey *et al.*, 2013; Nguyen, Young and Cooke, 2017), and the spread of technologies such as social media and decision-support tools bringing new opportunities for communicating science to decision-makers (Toivonen *et al.*, 2019; Rose *et al.*, 2021). Nevertheless, many core challenges remain the same. Major highlighted barriers for turning science into conservation action worldwide include gaps and bias in knowledge production, and mismatches in the thematic, spatial or temporal scope of research to the needs of decision-makers (Ferreira and Klütsch, 2021).

It is widely acknowledged that conservation science is useful in informing decisions when it is relevant to the priorities of the target decision-maker (Balmford, 2012; Rose *et al.*, 2018). It has also been demonstrated that relevance can be enhanced both by engaging with relevant stakeholders and having a clearly defined pathway from research output to implementation from an early stage in research design (Penfield *et al.*, 2014; Lavery *et al.*, 2021). Bi-directional flow of information between stakeholders (those affecting and affected by decisions) and scientists also promotes more robust decisions that are more likely to be supported and cooperated with (Mitton *et al.*, 2007; Hyman *et al.*, 2022; LeFlore *et al.*, 2022), enhancing long-term conservation success. It should be noted that poorly conducted stakeholder engagement has the potential to be counterproductive, but the overall effect on behaviour change is positive where engagement is consistent, transparent, and influences decisions (Sterling *et al.*, 2017).

The risks posed to biodiversity from this continued failure to bridge the science-implementation gap are likely to intensify with the rapid increase in rate of scientific output (Plume and Van Weijen, 2014) and increasing urgency of global crises. The rate of scientific publishing across disciplines and in conservation continues to increase (Li and Zhao, 2015). A simple search of the database SCOPUS using the terms '(Biodiversity OR species) AND conservation' returned 230,032 documents published since 1970, of which 58% were published after 2013. Inappropriate use of evidence in conservation decision-making has been linked to sub-optimal allocation of financial, physical, or human resources and decisions that are counterproductive to the conservation objective (Miller, Agrawal and Roberts, 2013; Waldron *et al.*, 2013; Rose *et al.*, 2019). Underuse also wastes valuable research resources (Buxton *et al.*, 2021). The overall volume of research literature combined with sometimes contradictory terminology or findings makes it increasingly difficult for decision-makers to find, translate, and assimilate relevant information into effective conservation decisions (Pullin *et al.*, 2020). Therefore, the rate of evidence expansion could far exceed the rate of implementation. Understanding and bridging this gap is critical to the effective implementation of the Kunming-Montreal Global Biodiversity Framework.

1.1.4. New approaches to tackle evolving challenges

Evidence synthesis has arisen in response to the need to make evidence accessible to decision-makers (Pullin and Knight, 2009). Developed in the medical sciences, evidence synthesis describes a suite of tools for systematically collecting and summarising information from the existing literature into a form that is more accessible to decision makers (Pullin *et al.*, 2020). Evidence syntheses can take multiple forms. Systematic maps are suited to multi-faceted questions where an understanding of the distribution of knowledge is the aim (James, Randall and Haddaway, 2016). Alternatively, systematic reviews, especially those that apply meta-analysis techniques, are best suited to summarising the findings from studies that all investigate the same question (Haddaway and Pullin, 2014). Both utilise systematic searching and screening to decrease bias and promote transparency in the findings (James, Randall and Haddaway, 2016). The use of such approaches can consolidate a large and contradictory literature-base, providing clearer direction to inform decisions.

Given the increasing volume of literature, automated and semi-automated text analysis presents a valuable tool to efficiently extract and analyse large amounts of information. Due to the long periods of time between research publication and realised impact, studies on the effectiveness of tools to overcome the research-implementation gap often take a case-study approach (Sterling *et al.*, 2017). Another option is to monitor the use of recommended tools such as the clear framing of intended outcomes and the manner of stakeholder involvement in the research development at the point of research publication. Text analysis presents the opportunity to extract and analyse this data efficiently over a large number of studies. Text analysis has been used for identifying outcomes and recommendations in other fields (Tellería *et al.*, 2014; Guerreiro and Rita, 2020; van Laar *et al.*, 2020; Ahadh, Binish and Srinivasan, 2021) and the use of such techniques is expanding in ecology and conservation generally (Farrell *et al.*, 2022). However, the application of text analysis to monitor intended conservation outcomes and stakeholder involvement has not yet been attempted.

1.2. Thesis aims

The aim of my thesis was to understand available knowledge of the spatial distribution of threats to species globally and its accessibility and relevance to management and policy decisions. I achieved this by:

a) Refining the definition of threat mapping and developing a protocol for a comprehensive thematic synthesis of existing literature;
b) describing the scope and extent of existing literature that maps threats to animal or plant species;
c) quantifying mismatches between available literature and conservation need (threat abatement potential); and
d) evaluating the intended outcomes and extent of stakeholder involvement in the design and delivery of existing threat mapping research.

1.3. Thesis outline

The core/data chapters of this thesis cover the following:

In Chapter 2 the term 'threat mapping' research was refined to only include studies that visually presented the spatial co-occurrence of threatening human activities and susceptible wild species. Here, 'pressures' are considered to be the human activities and direct human-initiated processes that have the potential to become 'threats' where they interact with wild species. This included studies that measured susceptibility or impact but doing so was not required to be considered a threat mapping study. I then present a rigorous, transparent protocol for collecting available threat mapping literature according to this definition, and assessing the geographic, taxonomic, and thematic distribution of available evidence. Chapter 2 was published in the journal of environmental evidence (Ridley, McGowan and Mair, 2020).

In Chapter 3, I applied the protocol from Chapter 2 and present a thematic synthesis of the literature that maps threats to species. Over 14,000 unique documents were found across six peer-reviewed and grey literature sources, of which 1,069 contained applications of threat mapping. Threat mapping studies were classified according to 22 attributes to characterise the threats, populations, geographic scope, and methodologies applied. Evidence was unevenly distributed among all considered characteristics. Particular gaps in knowledge are highlighted in the areas of cumulative threats, land-based threats to marine systems, and threats to plants or the freshwater realm. Chapter 3 was published in the journal of environmental evidence (Ridley *et al*., 2022) with an accompanying online interactive database of relevant threat mapping studies (available at: https://naturalandenvironmentalscience.shinyapps.io/ThreatMapping_SM/).

Chapter 4 presents the argument that without data on conservation need it cannot be concluded whether an observed lack of research represents a gap to be filled or an appropriate allocation of limited resources. To assess this, I compared the distribution of threat mapping research effort to threat abatement potential using the species threat abatement and restoration (STAR, Mair *et al.*, 2021) metric for mammal and bird species. This revealed an urgent shortage of information on where agriculture and aquaculture, and biological resource use impact species in tropical regions of the Americas, Asia, and Madagascar. This analysis also highlighted the need for a fairer distribution of research effort among threats in continental Africa. Above all, this chapter can be used to guide objectively future study selection where the aim is to abate threats with the greatest potential to reduce species extinction risk.

Finally, I developed and tested a semi-automated approach to retrieve and classify statements of intended outcomes and stakeholder involvement from the text of threat mapping articles (Chapter 5). The approach was then used to investigate what the intended outcomes of threat mapping studies are, the extent and manner of stakeholder involvement in the design and delivery of threat mapping research, and whether particular outcomes are associated with particular threats or stakeholder involvement. Studies that intended to inform biodiversity conservation planning generally were the most common, while outcomes on the theme of law and policy were the least prevalent. 155 sentences among 89 studies were found that indicated involvement of stakeholders. Among these, the key stages of research development: planning and process, data and inputs, and validation and verification, were roughly evenly represented.

Chapter 2: The scope and extent of literature that maps threats to species globally: a systematic map protocol.

*This chapter was published in the journal Environmental Evidence: Ridley, F.A., McGowan, P.J. and Mair, L. (2020) 'The scope and extent of literature that maps threats to species: a systematic map protocol'. *Environmental Evidence*, 9(1), pp. 1-9.

2.1. Abstract

Background: The rate of anthropogenic biodiversity loss far exceeds the background rate of species extinctions. Global targets for biodiversity acknowledge this, nevertheless progress towards targets has been poor. There is now a reasonable understanding of what human pressures threaten the survival of species. However, information on where these threats are impacting species is needed to coordinate conservation actions and threat abatement efforts. Herein, threats are defined as human-driven pressures specifically where they co-occur with, and threaten the survival of, native wild species. There is a large number of studies that map either distributions of threatened species or human-driven pressures alone. This makes it difficult to identify research that has investigated the spatial distribution of the threats themselves. Additionally, the high variability in approaches taken in these studies promotes a high risk of duplication and diversity among the findings. This variation, and the lack of studies directly mapping threats, limits the utility of threat mapping studies for conservation planning and informing policy. Therefore, a systematic consolidation of the literature is necessary to identify where knowledge is lacking, and where sufficient evidence exists for synthesis of the collective findings.

Methods: This protocol details the process for a systematic mapping exercise aiming to identify studies that map threats to species across the world. For a study to be included it should present spatially explicit data on both the occurrence of species and the human-driven pressures threatening them. A range of peer-reviewed and grey literature repositories will be searched in English for literature published 2000 - 2020, followed by one iteration of backward snowballing. A three-stage screening process will be implemented before data are extracted on geographic coverage, taxonomic extent, and threats investigated. Data on the threats studied will be categorised using the threat classification

scheme used by the IUCN Red List to allow comparisons among studies and to identify unrepresented threats. The extracted data will be analysed and visualised to describe the extent of existing knowledge. The resulting database of studies, findings from descriptive analyses, and accompanying narrative synthesis, will be made publicly available.

2.2. Background

Biodiversity is declining at a rate 100 to 1,000 times the background rate (Pimm *et al.*, 2014), fast approaching that of a mass extinction event (Barnosky *et al.*, 2011). Furthermore, the body of evidence to support the reliance of people on biodiversity is extensive (IPBES, 2019a), with ecosystem services having an estimated worth of US$125 trillion per year (Costanza *et al.*, 2014; WWF, 2018). Multiple global targets acknowledge the need to combat threats to species in order to achieve biodiversity outcomes (CBD, 2010). However, despite considerable progress made towards targets on protected land and sea areas, progress towards threat-specific targets has been poor, and species extinction rates continue to increase (IPBES, 2019a).

The threats to species around the world are numerous and diverse. Eighty percent of threatened or near-threatened species are impacted by more than one threat, the most frequent in IUCN Red List assessments was found to be overexploitation and agriculture (Joppa *et al.*, 2016; Maxwell *et al.*, 2016). Urban development, invasive species or disease, pollution, natural system modification, and climate change are also prevalent contributors to species' extinction risk (Joppa *et al.*, 2016; Maxwell *et al.*, 2016). Many of these activities result in land-use change, which has been found to have the highest relative impact on terrestrial and freshwater ecosystems (IPBES, 2019a). Threats to species are not distributed homogenously across the world. Schulze *et al.* (2018) found that fire system modification was the most frequently reported threat to African protected areas, in contrast to Eurasia and North America where the most frequently reported threats were recreational activities and invasive species respectively. In addition, experts estimated that coral reef ecosystems were most heavily impacted by climate change, over-fishing, and pollution (Halpern *et al.*, 2007). Meanwhile, freshwater ecosystems are subject to a suite of disruptions including water system modification, invasive species, and direct habitat loss due to the drainage of wetlands for development (Cazzolla Gatti, 2016). Therefore, information not only about what processes threaten species but how they are distributed spatially, is needed to identify and prioritise conservation actions.

2.2.1. The purpose of threat maps

Visualisations of the spatial distribution of threats to species (threat maps) have multiple, interrelated purposes that are closely linked to the spatial scale at which they are implemented. Threat maps are highly recommended in systematic conservation planning for deciding which actions to take where, and to prioritise limited resources (Margules and Pressey, 2000; Tulloch et al., 2015). Such plans tend to be localised and accompanied by techniques such as multi-criteria decision-making and cost-effective analysis (Carwardine *et al.*, 2012; Auerbach, Tulloch and Possingham, 2014). In a similar way, at national, international and global scales threat maps support conservation policies and projects by engaging with policy officials and the public for the provision of awareness and funding (Tulloch et al., 2015). For example, the Critical Ecosystem Partnership Fund has awarded over US$231.9 million in grants specifically to conservation projects in Biodiversity Hotspots since 2000 (Myers *et al.*, 2000; CEPF, 2018). Eighty percent of threatened species rely on either conservation at multiple sites, or a combination of site and landscape scale action (Boyd *et al.*, 2008). Therefore, all scales of threat mapping application, from local to global, are vital to preventing species extinctions.

A widespread conservation strategy with strong political traction is the demarcation and management of protected areas. This has variable effectiveness on conservation outcomes depending on whether the underlying threats are concurrently addressed (Mora and Sale, 2011; Pfeifer *et al.*, 2012; Geldmann, Joppa and Burgess, 2014; Jones *et al.*, 2018). Often overexploitation continues in protected areas despite political and legal restrictions (Golden, 2009; Golden and Knightes, 2011; Dureuil *et al.*, 2018). However, the strict no-extraction policies recommended for optimum protected area management (Edgar *et al.*, 2014), are unfeasible where human communities rely on natural resources for their basic wellbeing (Oldekop *et al.*, 2016). Furthermore, many threatened species are widely distributed outside protected areas (Rodrigues *et al.*, 2004; Noss *et al.*, 2012; Dinerstein *et al.*, 2017; Dudley *et al.*, 2018; Magris and Pressey, 2018). Therefore, the knowledge of the spatial distribution of threats to species, both inside and outside protected areas is required to aid effective reserve management and inform wider landscape-scale conservation.

2.2.2. Redefining threat mapping

The range of terms used in the literature makes it difficult to pinpoint research that explicitly links the spatial distribution of threats to where species occur. The term 'threat mapping' has been broadly used to describe any spatial representation of the distribution, intensity or consequences of threat. Therefore, it has been used to refer to anything from hotspots of threatened species richness, or extinction risk categories (Brooks *et al.*, 2006; Wilson *et al.*, 2006; Geldmann, Joppa and Burgess, 2014), to the distribution of human-driven pressures irrespective of species presence (e.g. The Human Footprint Index (Sanderson *et al.*, 2002; Venter *et al.*, 2016a). For example, of four global prioritisation frameworks that included a measure of threat (Brooks *et al.*, 2006), biodiversity hotspots (Myers *et al.*, 2000), last of the wild (Sanderson *et al.*, 2002), Crisis ecoregions (Hoekstra *et al.*, 2005), and High biodiversity wilderness areas (Mittermeier *et al.*, 2003), none showed where species and threatening human activities co-occurred. Meanwhile, Di Marco *et al.* (2019) represents a valuable advancement in threat mapping research, yet also does not provide this information. Their predictions for the probability of species persistence were based on beta-diversity and abiotic environment rather than threatening human activities. Contrastingly, Allan *et al.* (2019) combined data on human-driven pressures from the Human Footprint Index with threat and species distribution data from the IUCN Red List, revealing areas of active threat and refuges from threat. Furthermore, some studies use alternative words such as 'stress', 'impacts', or 'footprints' to describe threats to species (Brown *et al.*, 2014; Comte and Olden, 2017; Allan *et al.*, 2019), making it easy to overlook relevant evidence. Therefore, a revision in terminology is useful here, in order to distinguish maps that show the spatial coincidence of species and their threats from other representations of threat.

Part of the variability in terminology use comes from the fact that, although previous definitions distinguish between stress and impacts, pressures and threats are generally considered synonymous. Salafsky *et al.* (2008) considered threats (or pressures) to be the direct human activities or processes that result in stress to species, where stress is a change in a species' ecological environment beyond normal levels of variation that compromises its survival. High densities of threatened species do not occur in every location where humans exert pressure on the landscape (Venter *et al.*, 2016b; Allan *et al.*, 2019). Meanwhile, some species are tolerant to human pressure (Rosset and Oertli, 2011). Therefore, here 'pressures' are considered to be the human activities and direct human-initiated processes that have the potential to become 'threats' where they come into contact with wild species. Consequently, for the sake of this study, threat mapping research is considered that which describes or analyses the spatial distribution of threats to species. In other words, the spatial coincidence of wild populations of species and the human-driven pressures threatening them.

As the main purpose of threat mapping is to understand where threats occur, the findings must be projected onto a geographic distribution and presented spatially. Consider a study that investigates the effect of a threat on a species at a particular study site by gathering data on pressure intensity (x) and species abundance (y). If the study tested for a relationship between x and y without presenting a georeferenced spatial visualisation of how they varied across the study site, it would not be considered a threat mapping study. This is because the study itself did not present data on where geographically the species and human-driven pressure co-occurred.

2.2.3. Identifying the gaps

Consolidation of the threat mapping literature is a vital next step towards understanding the distribution of threats to species globally. A high diversity of approaches are present in the existing literature; varying in spatial extent, number and types of threats included, data types used, and specific questions asked (Fuller *et al.*, 2010; Evans, Possingham and Wilson, 2011; Parravicini *et al.*, 2012; Brown *et al.*, 2014; Gallardo, Zieritz and Aldridge, 2015; Gaisberger *et al.*, 2017; Moran and Kanemoto, 2017; Allan et al., 2019; Chaudhary and Brooks, 2019). A diverse and fragmented literature base presents a high risk of duplication of research effort and diversity among the findings, as shown in related fields. For example, Orme *et al.* (2005) found low agreement among the findings of different biodiversity prioritisation frameworks. Meanwhile, Mace *et al.* (2000) called for collaboration in light of the already high levels of duplication in conservation prioritisation efforts. Therefore, the likelihood of duplication and contradictory findings within the, yet uncharacterised, threat mapping literature is high. This would compromise a major purpose of threat maps, to prioritise limited resources for threat abatement action and awareness. Therefore, there is a need to locate gaps in knowledge, and identify where sufficiently similar evidence exists to facilitate synthesis of the collective findings.

It is likely that not all threats are equally represented in the literature. Threat mapping largely relies on satellite data and this reliance creates inherent biases in the types of threats considered in the existing literature (Sanderson *et al.*, 2002; Evans, Possingham and Wilson, 2011; Venter *et al.*, 2016a). For this reason, threats such as overexploitation are likely to be underrepresented in spatial analyses of threats (McGowan, 2016), despite being the most frequently reported threat in IUCN Red List assessments (Maxwell *et al.*, 2016). In addition, Joppa *et al.* (2016) found that biological resource use accounted for only 5% of datasets on species threats globally. Furthermore, despite often being studied spatially (Welk, Schubert and Hoffmann, 2002; Zhu *et al.*, 2007; Clarke Murray *et al.*, 2014), invasive alien species were only included in three cumulative threat assessments found in preliminary literature searching (Halpern et al., 2008; Reddy *et al.*, 2014; Allan *et al.*, 2019). To the authors' knowledge no systematic review of the literature analysing threats to species has been completed. Therefore, this work has significant potential to highlight gaps in knowledge of high benefit to threat abatement efforts.

This protocol describes the procedure that will be taken in the systematic map to follow, which will aim to collect and characterise the existing threat mapping literature. Systematic mapping is an exercise of rigorously and transparently gathering information from the existing literature, and describing it using data visualisation and analysis tools. In contrast to a systematic review, which collects and synthesises data on the findings, systematic maps tend to investigate the scope and extent of the literature base (James, Randall and Haddaway, 2016). Previous applications in biodiversity conservation include: the impacts of conservation actions on human wellbeing (McKinnon *et al.*, 2016), outcome reporting in systematic conservation planning (McIntosh *et al.*, 2018), and the contribution of invasive species to biodiversity loss (Roberts *et al.*, 2013).

This systematic map is intended to fill a knowledge gap that has emerged during a wide range of discussions with diverse stakeholders during the development of the Post-2020 Global Biodiversity Framework. As the negotiations move towards an emphasis on biodiversity outcomes for species as a high-level goal and action targets that will address the pressures/threats on species, it is expected that the findings from this map will inform these negotiations and implementation of the Framework when it is agreed.

2.3. Objectives of the Review

This work aims to describe the threat mapping literature by analysing data on the methodological, geographic, and taxonomic extent of existing studies that map the threats to species. Gaps and clusters in knowledge will be identified, and a searchable database of threat mapping studies with corresponding meta-data will be created. Historic threat distributions are outside the scope of this study, therefore only studies published in the previous 20 years will be included. Similarly, work projecting future distributions of threats and studies that are purely modelling, theoretical or lab-based will be excluded. Another possible approach to studying where threats occur could be to study the spatial extent of all existing literature studying threats. However this is outside the scope of this investigation.

2.3.1. Primary Question

The primary overarching question of this analysis is: What is the scope and extent of literature that maps threats to species?

2.3.2. Population

The taxonomic scope of this study is any species of animal or plant globally, in any country or ecozone (terrestrial, marine, and freshwater). Species presence must be evidenced for studies to be included in the analysis. This evidence could be the observed range of individual species, or a pre-defined priority area for biodiversity conservation, such as a Biodiversity Hotspot [see Appendix A.1]. A pre-defined priority area is defined as one that has been identified to be of conservation priority in previous work by other authors or organisations, due to its presence, richness, or density of species. Habitat suitability or other modelled species distributions can be used provided there is evidence of species presence within the study site.

2.3.3. Outcome

The outcome to be examined is the spatial distribution of threats to species. By our definition, threats occur where species are exposed to human-driven pressures. Thus, the focus here is on the distribution of threatening human activities and direct human-initiated processes rather than the ecological mechanisms (stressors) that subsequently impact the state of species [for examples see Appendix A.1]. This is because one stressor can be caused by multiple interrelated human or natural processes. For example, a spatially explicit investigation into the concentration of manufactured pesticide and pharmaceutical contaminants in waterways that are protected for biodiversity conservation, would qualify for inclusion (Bradley *et al.*, 2020). Whereas, an investigation measuring water quality indicators, without evidence of their anthropogenic source, would not be included (Zambrano *et al.*, 2009). Likewise, an investigation that observed species habitat conversion to specific human land-uses would qualify for inclusion. However, a study on habitat loss, with no further indication of the distribution of human activities responsible, would not be included. Studies measuring stress will only be included if the stress is explicitly a result of one or more threats and used as a proxy for those within the study.

To facilitate the consistent application of this definition throughout, the IUCN Red List threat classification scheme will be used as guide to categorise data on the threats studied in each article (IUCN, 2006; Salafsky *et al.*, 2008). This hierarchical framework categorises threats to species into 12 high level categories which collectively encompass 103 fine scale categories of threat (IUCN, 2006; Salafsky *et al.*, 2008). By doing so, threat mapping work using different methodologies and terminologies can be analysed together. Additionally, the use of the framework will reveal the proportional representation of different threats as well as any threats that are unrepresented within the literature base. Other classification schemes are more suited to capturing the complex interrelations between the activities, processes, and mechanisms driving species extinctions (Balmford *et al.*, 2009). However, as the purpose of this investigation is to catalogue existing evidence, the IUCN framework was deemed the most appropriate for this.

2.3.4. Study type

This work will specifically identify studies that consider where the distributions of species and human-driven pressures coincide. Therefore, the population and the outcome component must be studied spatially within a global extent. The range of methodologies present in the literature complicates this. For example, if the distribution of pressures within a landscape is studied, and mean threat within protected areas is presented in a non-spatial sub-analysis, this would not merit inclusion (e.g. Geldmann, Joppa and Burgess, 2014). This is because it does not inform as to where the points of contact between protected areas and human-driven pressures are. Whereas, if studies take pre-existing knowledge about the threats affecting a particular species (such as from IUCN Red List assessments), and project it onto the geographic distribution of that species, these would be included.

2.3.5. Secondary Questions

Further sub-group analyses will be structured around the following secondary questions:

1. What is the geographic distribution of the existing literature?
2. What is the taxonomic distribution of the existing literature?
3. Which threats are most frequently studied and how many different threats are considered in each study?
4. How has the extent of knowledge changed over time, and where do gaps and clusters in knowledge exist?

2.4. Methods

2.4.1. Searching for articles

2.4.1.1. Scoping

Fifteen relevant papers were chosen from preliminary reading to comprise the 'test-list' to develop the search and compare the comprehensiveness of searches against (Booth, Sutton and Papaioannou, 2016). These were chosen based on their ability to capture the scope and diversity of terminology in the literature base [Appendix A.2]. Keywords were extracted along with unofficial keywords present in the title and abstract of these papers where designated keywords were unavailable. The keywords were grouped into terms and a thesaurus (Dictionary.com, 2020) used to identify appropriate synonyms [Appendix A.2]. The search string was developed and tested using SCOPUS, with the minimum combination of broad terms required to yield the full test-list of articles used as a starting point. Generality of the search was increased by adding synonyms, while specificity was increased by substituting broad terms for specific alternatives [Appendix A.3]. The exclusion rates of two candidate searches were compared by performing a title-level screen to determine the final search string [Appendix A.2].

2.4.1.2. Comprehensiveness of search

The comprehensiveness of each individual search attempted was tested against its ability to return the test-list of fifteen benchmark articles [see Appendix A.3]. This was done to ensure that all searches considered met the baseline threshold for comprehensiveness. The first candidate search tested yielded 5,679 articles in SCOPUS, of which 54% were excluded after a title-level screen. Whereas, the second candidate search yielded 10,463 articles in SCOPUS, of which 57% were excluded. The latter search was chosen as the final search string because 1,859 more potentially relevant articles were found, approximately four for every ten additional articles that were screened [Appendix A.2]. This was deemed to support the choice of this search string as a balance of specificity and sensitivity. The final search yielded 28,990 results across the five published and grey literature databases proposed [Appendix A.2]. Therefore, a more sensitive search was not considered.

The final search string will be used to search publication databases, search engines and grey-literature repositories in English for articles published between 2000 and 2020. This time period was chosen as current, rather than historic or future, threat distributions are the focus of this investigation. It is recognised that local-scale studies from non-English speaking countries are likely to be overlooked however, restricted translation resources mean the inclusion of multiple languages is not feasible.

2.4.1.3. Search terms

The final search string is as follows:

(pressure OR threat OR risk OR stress OR footprint) AND (species OR ecosystem OR wildlife OR fauna OR flora OR “spp.” OR “sp.”) AND (hotspot* OR map* OR geographic* OR "gis" OR "spatial distribution" OR "spatial overlap" OR "spatial separation" OR "spatial dynamics" OR "spatial variation" OR "spatial framework" OR "spatially explicit" OR geospatial) AND (conservation OR biodiversity)

Publication databases to search

SCOPUS, ProQuest natural science collection, and Web of Science Core collection will be searched for published peer-reviewed studies by title, abstract, and keywords. The final search performed using these three databases collectively yielded 28,097 articles (10,462, 8,859, and 8,776 respectively), of which 13,933 were found to be unique. As the number of unique results is greater than any single search, all three will be used to search for published literature. All searches will be performed using the subscription of Newcastle University. For specifics of the subscription and how each database will be searched see Appendix A.2.

2.4.1.4. Search engine

Google Scholar will be used to identify grey literature using the simplified search of: (pressure OR threat OR footprint) AND (species OR ecosystem OR wildlife). The title only will be used to search for literature on google scholar as this has been found to be more efficient than searching the full text (IUCN, 2020). The first 500 results will be gathered in order of relevance.

2.4.1.5. Grey literature searches

To find grey literature ProQuest Natural collection will be specifically searched for non-peer reviewed Dissertations & Theses, Government and official publications, reports, and working papers using the same search string as the published literature search.

2.4.1.6. Organisational websites

The following organisational websites will be searched using the word 'threats'. The word 'threats' resulted in the same or more results than the word 'threat' across almost all websites. The only exception was Blue Ventures (Ventures, 2020) for which 'threat' returned more, and so this website only will be searched using the word 'threat' instead.

- WWF, World Wildlife Fund (WWF, 2020)
- UNEP-WCMC (UNEP-WCMC, 2020)
- CBD, Convention on biological Diversity (CBD, 2020b)
- IUCN, International Union for the Conservation of Nature (IUCN, 2020)
- IPBES, Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES, 2020)
- RSPB (RSPB, 2020)
- Fauna and Flora International (Fauna-Flora, 2020)
- The Nature Conservancy (Conservancy, 2020)
- Conservation International (Conservation International, 2020)
- Birdlife International (BirdLife International, 2020)
- Blue Ventures (Ventures, 2020)
- The Audubon Society (Audubon, 2020)
- SCB, Society of Conservation Biology (SCB, 2020)

2.4.1.7. Targeted Searches

Backward snowballing will be used to identify additional studies, whereby the literature cited in all articles included after full-text screening will be collected. Previous work has found this technique to be twice as effective in identifying relevant articles as database searching (Badampudi, Wohlin and Petersen, 2015). The same procedure of duplicate removal and screening will then be applied to these articles.

2.4.2. Article screening and study eligibility criteria

2.4.2.1. Screening Process

A three-stage screening process (Title, Abstract, and Full-text) will be undertaken using EPPI-reviewer 4 (Thomas, Brunton and Graziosi, 2010). At each stage, articles will be compared against the eligibility criteria below. At the title stage if there is insufficient information presented to conclusively exclude a study, all studies pertaining to an effect of human-driven threats on species, or prioritising conservation efforts, will be screened again at abstract level. If at the abstract stage there is insufficient information to categorically exclude a study based on the eligibility criteria, it will be retained to the full-text stage. A record will be kept of all studies excluded at the full-text screening stage, reporting the reasons for their exclusion.

2.4.2.2. Consistency checking

The screening process will be predominantly carried out by one core reviewer. At each screening stage (title, abstract, and full-text) a random 20% of articles, to a minimum of 50, will be selected for second review and Kappa analysis. Cohen's Kappa will be used to calculate the proportional agreement between the two reviewers with two outcome categories 'Include' or 'Exclude', and accounting for the agreement expected by chance (Cohen, 1960). Any disagreements will be discussed between reviewers and a decision whether to include or exclude the articles made. If the resulting kappa statistic is less than 0.6, the robustness of the eligibility criteria will be re-considered (McHugh, 2012). None of the reviewers are expected to author any articles to be considered within the review.

However should the situation arise, this will be declared and detailed reasoning for all decisions regarding the articles in question will be reported.

2.4.2.3. Eligibility criteria

1. Eligible population: The taxonomic scope of this study is any species of animal or plant globally, in any country or ecozone (terrestrial, marine, and freshwater). Species presence must be evidenced for studies to be included in the analysis. This evidence could be the known range of species, or a pre-defined priority area for biodiversity, such as a protected area or Biodiversity Hotspot. In all instances where a pre-defined metric is used, the presence of species must be a qualifying criteria of that definition for the study to be included. Examples of protected areas and priority areas for biodiversity that do, and do not, meet this criteria are given in Appendix A.1. Similarly, habitat suitability or other modelled species distributions can be used provided there is evidence of species presence within the modelled distribution.

a. Excluded if: No evidence is given for the distribution or presence of relevant species within the study area.

b. Excluded if: The study models habitat suitability on purely ecological factors without evidence of species presence at the study site e.g. for the purpose of reintroduction.

2. Eligible outcome: the spatial distribution of threats to species. Threats occur where species populations are exposed to human-driven pressure. Whereby, human-driven pressures are the activities and human-initiated processes that have the potential to negatively impact the ecological fitness of species. Where studies include multiple ‘threats’, at least one must fit the definition of a threat used here for the study to be included. If the threats included fit the definition of threats used here but cannot be assigned to one of the IUCN threat classification scheme categories, then “Other” will be assigned. The distribution of multiple threats can be presented individually or as a composite index. Where invasive alien species are considered, the distribution of the invasive alien will be considered the threat distribution.

a. Excluded if: No data on where species and human-driven pressures co-occur is presented e.g. measuring threatened species richness.

b. Excluded if: ecological stress is measured without being explicitly considered a valid proxy for a specific threat.

c. Excluded if: the threat considered is listed in the IUCN threat classification scheme but is not necessarily a result of human action (e.g. geological events). Studies on threats such as fire, extreme weather, and disease, should only be included if they are specifically human-induced in the context of the study.

3. Eligible study types: only primary research published 2000 - 2020 in English will be included, which may use either primary data, or pre-existing datasets. Exceptions can be made in the case of systematic reviews and meta-analyses where data from primary work has been collated and re-analysed. Only studies assessing current threat distributions will be included, as opposed to projected future distribution or historic distributions.

a. Excluded if: The article is a narrative review in which no new synthesis of data is being presented.

b. Excluded if: The displayed distribution is projected forward in time or describing historic threat distributions.

c. Excluded if: The threat distribution is not within a global spatial extent whether theoretical or due to insufficient reporting.

2.4.3. Study validity assessment

Validity of individual studies will not be assessed beyond study eligibility based on the above criteria. Information on the study designs and data types used will be coded, allowing for future assessment of the validity of those methods.

2.4.4. Data Coding Strategy

Coding of the articles included at the full-text stage will be completed by filling in a pre-designed data collection sheet with discrete fields for data entry, for which McIntosh *et al.* (2018) has been used as a template. The data sheet was tested using the fifteen-article test-list to assess usability and clarity [see Appendix A.4]. 20% of articles will be randomly chosen to be coded by a second reviewer. Any discrepancies will be discussed, and decisions about the correct coding to apply will be made collaboratively between reviewers.

Data will be extracted from the articles on bibliography, study design, threat measurement, and population studied. Data collected must be presented within the article or the additional material to be coded. Authors will not be contacted regarding missing information. The IUCN Red List threat classification scheme will form the typology for coding data on the number of, and which specific threats were studied in each article. Of these the twelfth high level category is "Other" and therefore, all human-driven threats will be accounted for. Information relating to population will be gathered with regards to the measure for species presence used, in addition to the taxonomic extent and resolution.

2.4.5. Study Mapping and Presentation

The findings will be published in this journal along with a searchable database of articles and the corresponding coded meta-data. Detailed information on the flow of articles through the process will be included, including the number of papers acquired from each source and those excluded at each stage. A geographic map will be produced detailing the coverage and density of study areas across the world, also displaying the distribution of studies among different spatial scales.

The taxonomic distribution of existing research will be visualised by plotting taxonomic groups against taxonomic resolution, whereby the response value will be the number of studies satisfying the two conditions. This will highlight if, for example, most studies on threats to plants take a kingdom wide approach, whilst most studies on mammals are family or genus specific. The mean number of threats considered per study will be presented with variance given, in addition to frequencies of occurrence of each threat category. Linkages between spatial distribution, taxonomy, and threats studied will be evaluated using co-occurrence matrices. The report will be complemented by a narrative synthesis discussing the range of approaches implemented, and avenues for future research.

Chapter 3: The scope and extent of literature that maps threats to species globally: a systematic map.

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3.1. Abstract

Background: Human activities are driving accelerating rates of species extinctions that continue to threaten nature's contribution to people. Yet, the full scope of where and how human activities threaten wild species worldwide remains unclear. Furthermore, the large diversity of approaches and terminology surrounding threats and threat mapping presents a barrier to understanding the state of knowledge and uptake into decision-making. Here, we define 'threats' as human activities and direct human-initiated processes, specifically where they co-occur with, and impact the survival of, wild species. Our objectives were to systematically consolidate the threat mapping literature, describe the distribution of available evidence, and produce a publicly available and searchable database of articles for easy uptake of evidence into future decision-making.

Methods: Four bibliographic databases, one web-based search engine, and thirteen organisational websites were searched for peer-reviewed and grey-literature published in English 2000-2020. A three-stage screening process (title, abstract, and full-text) and coding was undertaken by two reviewers, with consistency tested on 20% of articles at each stage. Articles were coded according to 22 attributes that captured dimensions of the population, threat, and geographic location studied in addition to methodological attributes. The threats studied were classified according to the IUCN Red List threat classification scheme. A range of graphical formats were used to visualise the distribution of evidence according to these attributes and complement the searchable database of articles.

Review Findings: A total of 1,069 relevant threat mapping articles were found and included in the systematic map, most conducted at a sub-national or local scale. Evidence was distributed unevenly among taxonomic groups, ecological realms, and geographies. Although articles were found for the full scope of threat categories used, most articles mapped a single threat. The most heavily mapped threats were alien invasive species, aquatic or terrestrial animal exploitation, roads and railways, residential development, and non-timber crop and livestock agriculture. Limitations regarding the English-only search and imperfect ability of the search to identify grey literature could have influenced the findings.

Conclusions: This systematic map represents a catalogue of threat mapping evidence at any spatial scale available for immediate use in threat reduction activities and policy decisions. The distribution of evidence has implications for devising actions to combat the threats specifically targeted in the post-2020 UN Biodiversity Framework, and for identifying other threats that may benefit from representation in global policy. It also highlights key gaps for further research to aid national and local-scale threat reduction. More knowledge would be particularly beneficial in the areas of managing multiple threats, land-based threats to marine systems, and threats to plant species and threats within the freshwater realm.

3.2. Background

Species extinctions are occurring at up to 1,000 times the background rate (Pimm *et al.*, 2014; De Vos *et al.*, 2015), and for some taxa these rates are now comparable to previous mass extinction events (McCallum, 2021; Neubauer *et al.*, 2021; Schachat and Labandeira, 2021). Unlike the five previous events that were prefaced by large-scale geological and climatic changes, the current pulse of extinction is being driven by human activities (Barnosky *et al.*, 2011; Payne *et al.*, 2016; Keller *et al.*, 2018). Yet, biodiversity contributes vital services to humanity such as climate regulation, food production, and clean water and air provision (Costanza *et al.*, 2014; Brondizio *et al.*, 2019). Therefore, it is imperative that the human-driven threats to species are reduced to bend the curve of biodiversity loss (Leclere *et al.*, 2018; Mace *et al.*, 2018).

Spatial prioritisations are a useful tool for informing a variety of conservation practice and policy interventions. For example, mapping is a highly recommended part of a systematic conservation planning process, and can help to identify where to carry out specific actions and prioritise limited financial and physical resources (Margules and Pressey, 2000; Tulloch et al., 2015; Tulloch *et al.*, 2020). These maps tend to be local in scope, and coupled with multi-criteria decision making or cost-effective analyses (Carwardine *et al.*, 2012; Auerbach, Tulloch and Possingham, 2014). On the other hand, multi-national and global-scale conservation priority maps have the power to generate public and policy awareness to deliver large amounts of funding to conservation projects in particular areas (Brooks *et al.*, 2006; Tulloch et al., 2015). For instance, the Critical Ecosystem Partnership Fund awarded US$255 million to conservation projects in Biodiversity Hotspots (Myers *et al.*, 2000) between 2000 and 2020 (CEPF, 2020). Therefore, conservation priority maps at different scales have differing but equally important functions for conserving biodiversity.

The term 'threat mapping' has been used to refer broadly to any spatial representation of the occurrence, intensity, or consequence of threat or threats (Tulloch et al., 2015). This means that the term 'threat mapping' has been applied equally to maps of threatened species or extinction risk categories (herein maps of species state, e.g. Myers *et al.*, 2000; Orme *et al.*, 2005; Brooks *et al.*, 2006; Wilson *et al.*, 2006; Di Marco *et al.*, 2019), maps of human-driven activities irrespective of species presence (herein maps of human pressure, e.g. Sanderson *et al.*, 2002; Venter *et al.*, 2016a; Venter *et al.*, 2016b), and maps of the spatial co-occurrence between species and threatening human activities (herein threat maps, e.g. Allan *et al.*, 2019). Threat mapping for spatial prioritisation has been criticised as being insufficient for making effective conservation decisions (Tulloch *et al.*, 2015), yet such critiques have not distinguished between the types of maps described here. Of these three, the latter (threat maps) and their underlying data have the greatest potential to inform threat reduction actions but the availability, characteristics, and utility of which has not yet been discussed or formally reviewed.

A lack of standardised terminology in the literature surrounding threat maps makes the process of finding relevant maps arduous, representing a barrier to understanding the state of knowledge and to uptake in conservation planning and policy decisions. This is not limited to mapping approaches but also pervasive in the definition of threats themselves, for which 'stress', 'impacts', 'risk' , 'drivers' and 'footprints' are often used synonymously (Brown *et al.*, 2014; Comte and Olden, 2017; Brown and Hamilton, 2018; Allan et al., 2019).

Furthermore, many authors refer to processes such as habitat loss and land-use change as a threats (Jetz, Wilcove and Dobson, 2007; Trisurat *et al.*, 2010; Powers and Jetz, 2019; Davison, Rahbek and Morueta-Holme, 2021). Whereas, others consider these processes to be the mechanism by which threatening human activities result in species declines rather than being threats themselves (Salafsky *et al.*, 2008; Balmford *et al.*, 2009). Rigorous systematic review processes can overcome such variation in language; however, these can be time-consuming, and conservation planning and policy decisions are often made on timescales too short to accommodate their findings (Sutherland *et al.*, 2020a).

A clarification in terminology is useful here to distinguish maps that: a) show the spatial coincidence of species and threatening human activities, from b) other spatial representations of threat. Here, 'pressures' are considered to be the human activities themselves that have the potential to become 'threats' where they adversely affect wild species. Consequently, threat mapping literature is that which presents the geographic occurrence of threats to species. For example, a study investigating the effect of a human-pressure (x) on a population of species (y) would not be considered a threat mapping study unless it visually presented the geographic distribution of x and y within the study area. In other words, threat mapping research is any investigation that presents the geographic co-occurrence of wild populations of species and the human-driven activities that negatively impact them.

Consolidating and describing the characteristics of the threat mapping literature is a vital next step towards understanding where and how human activities threaten species globally. A diversity of approaches are present in the threat mapping literature, including a range of spatial scales, threats studied, taxonomic groups, and questions asked (Fuller *et al.*, 2010; Evans, Possingham and Wilson, 2011; Brown *et al.*, 2014; Allan et al., 2019; Chaudhary and Brooks, 2019). In addition, the quantity of scientific literature inside and outside conservation science has increased considerably in recent years and continues to do so (Ware and Mabe, 2009; Plume and Van Weijen, 2014; Li and Zhao, 2015; Pullin *et al.*, 2020). A simultaneously numerous and fragmented literature contributes to the barrier between research and implementation (Pullin *et al.*, 2020) and presents a high risk of research effort duplication and contradictory findings, as demonstrated in related fields (Mace *et al.*, 2000; Orme *et al.*, 2005). Moreover, unidentified gaps and clusters in knowledge can result in a distorted understanding of a system (Hughes, 2019; Hughes *et al.*, 2021; Sobral-Souza *et al.*, 2021), thus increasing the likelihood that decisions based on such knowledge are flawed. Therefore, given that a major purpose of threat maps is to prioritise limited resources for threat abatement action and awareness, there is an urgent need to consolidate the, yet uncharacterised, threat mapping literature.

There is extensive evidence that research effort in conservation science varies among taxonomic groups (Seddon, Soorae and Launay, 2005; Darwall *et al.*, 2011; de Lima, Bird and Barlow, 2011; Trimble and van Aarde, 2012; Walsh *et al.*, 2013; Brooke *et al.*, 2014; Donaldson *et al.*, 2016; Fleming and Bateman, 2016; de Barros *et al.*, 2020; dos Santos *et al.*, 2020; Hughes *et al.*, 2021), and some evidence for variation among geographic locations (de Lima, Bird and Barlow, 2011; Trimble and van Aarde, 2012; Donaldson *et al.*, 2016; de Barros *et al.*, 2020; Hughes *et al.*, 2021). Additionally, it is expected that not all threats will be equally represented within the threat mapping literature, however, to our knowledge, there are no articles that consider differences in conservation research effort among threats. As threat mapping often relies on satellite data, threats that have a remotely observable footprint are expected to be disproportionately prominent in the literature (Sanderson *et al.*, 2002; Evans, Possingham and Wilson, 2011; Venter *et al.*, 2016a). Whereas, direct exploitative threats are likely to be underrepresented (Joppa *et al.*, 2016; McGowan, 2016), despite biological resource use being the most frequently reported threat in IUCN Red List assessments (Maxwell *et al.*, 2016). Furthermore, despite many spatial articles (Welk, Schubert and Hoffmann, 2002; Zhu *et al.*, 2007; Clarke Murray *et al.*, 2014), alien invasive species were included in only three cumulative threat assessments found during our protocol development (Halpern et al., 2008; Reddy *et al.*, 2014; Allan et al., 2019). Therefore, this work has the potential to highlight gaps in knowledge of high benefit to threat abatement efforts.

This systematic map of the literature describes the review process undertaken, the distribution of threat mapping evidence across the world, and the searchable database of threat mapping articles. The systematic map is intended to fill a knowledge gap that has emerged during a wide range of discussions with diverse stakeholders during the development of the Post-2020 Global Biodiversity Framework. Due to the emphasis on reducing the direct threats to species in the post-2020 framework, it is expected that the findings of the map and database of articles will inform these negotiations and the implementation of the framework when it is agreed. The systematic map was produced according to the published protocol (Ridley, McGowan and Mair, 2020), with only minor adjustments to the search strategy and eligibility criteria needing to be made, which are described in full and justified below.

3.3. Objectives of the Review

The aim of the systematic map was to describe the current distribution of threat mapping literature by collecting and analysing data on the methodological, taxonomic, and geographic extent of articles that have mapped threats to species. Descriptive analyses were used to identify gaps and clusters in knowledge to complement the publicly available database of articles and corresponding meta-data. As the scope of this investigation was existing in-situ threats, any articles published before 2000, articles of historical, future, or potential threats, and theoretical, captive, or lab-based articles were excluded. Furthermore, this analysis specifically considered threat mapping articles, therefore only articles that presented geographic distributions of both the threats and the affected species were included. Examples of how threat maps can be presented are given in Appendix B.1.

3.3.1. Primary Question

What is the scope and extent of literature that maps threats to species?

The following are the question elements:

3.3.2. Population

The taxonomic scope was any wild animal or plant species globally, in any ecological realm (terrestrial, marine, freshwater). Accepted proxies for the presence of species are detailed in the eligibility criteria.

3.3.3. Outcome

The outcome examined was the spatial occurrence of threats. Threats are considered to occur where threatening human activities or direct human-initiated processes co-occur with, and negatively impact, wild species. It is emphasised that the focus of this study was the direct human-driven activities and processes rather than indirect processes or the ecological mechanisms (stressors) that subsequently impact species. For example, articles mapping the occurrence of human-wildlife conflict where the subject of the measured impact was not the wild species (e.g. the impacted subject was human), or articles mapping freshwater quality indicators without specifying a human source of pollution, did not merit inclusion. In contrast, articles mapping retaliatory killing of predators by humans or those mapping agricultural or industrial effluent where species were observed, would both qualify for inclusion.

The IUCN Red List threat classification scheme (Salafsky *et al.*, 2008) was used as a guide to categorise the threats studied in each article in a consistent and coherent manner. This allowed threat maps using different methodologies and terminologies to be analysed in the same way, and any threats in the IUCN classification scheme that were unrepresented in the threat mapping literature could be identified. There is evidence to suggest that some of the threats may interact with one another (Auerbach, Tulloch and Possingham, 2014; Doherty *et al.*, 2015; Tulloch, Chadès and Lindenmayer, 2018; Geary *et al.*, 2019), which the chosen framework did not capture. However, as the purpose of this investigation was to catalogue the existing evidence, the IUCN threat classification scheme was deemed to be the most appropriate framework to use.

3.3.4. Methods

Any primary research that collected and presented data on the geographic occurrence of threats was considered within the scope of this investigation. This included georeferenced presentations of direct or remote observations, spatial modelling results, expert elicitation processes, existing data such as from the IUCN red list or museum archives, or data collected from existing literature. Similarly, all cartographic methods were within the scope. Whereas, schematic representations of the occurrence or gradient of threats without a specific geographic context were outside the scope.

3.3.5. Secondary questions of the systematic map

Descriptive analyses for the systematic map were structured around the following secondary questions:

1. What is the geographic distribution of the existing literature?
2. What is the taxonomic distribution of the existing literature?
3. Which threats are studied most frequently and how many different threats are considered in each study?
4. How has the extent of knowledge changed over time
5. Where do gaps and clusters in knowledge exist?

3.4. Methods

The following outlines the searching, screening, and data extraction process in the production of the systematic map. This was carried out in accordance with the published protocol (Ridley, McGowan and Mair, 2020). The few changes to the protocol that were made are described and justified below, before describing in full the method that was used in the relevant sub-sections.

3.4.1. Deviations from the protocol

1. An alternative strategy was adopted to search some organisational websites. Searches conducted via (internal) website search boxes often generated materials irrelevant to this protocol, such as press releases and educational resources. Some websites also had additional filtering features to aid search efficiency and a publications page on the website, separate to the search function. Therefore, where the proposed search was found to be inefficient and other such tools were available, an alternative strategy was used. The specifics of how each organisational website was searched and screened were recorded (Appendix B.2).

2. The criteria for including articles at title level was expanded as many potentially relevant articles would have been excluded under the previous guidance. In the protocol it was stated that 'if there was insufficient information present in the title to conclusively

exclude a study, all articles pertaining to an effect of human-driven threats on species, or prioritising conservation efforts will be screened again at abstract level'. Yet at the title screening stage, this guidance was found to be too restrictive. For example, titles that described the spread of human-driven pressure without referring to species, or those titled as conservation status assessments would have been excluded at this stage under the previous guidance. Therefore, expanding the scope of titles included at this stage was deemed necessary. The updated guidance related to inclusion of articles at title level is described fully in 'Article screening and eligibility criteria'.

3. Exclusion criteria 2B was changed from "Excluded if ecological stress is measured without being considered a proxy for a particular human activity" to "Excluded if the threat studied is relevant and studied in-situ but the occurrence was not mapped onto a geographic distribution". When applying the criteria it was found that the original criteria 2B was already represented under criteria 2A, whereby articles were excluded due to an absence of data on a relevant threat. Meanwhile, articles that undertook an otherwise relevant piece of research but did not present the findings in a spatially explicit way were abundant. Therefore, the new structure to the eligibility criteria was considered to better represent the reasons why articles were excluded.

4. The protocol included one subsequent round of snowballing within the search strategy. Snowballing was piloted on a sample of 574 articles (54% of the total relevant articles), in which all the literature cited in this sample was collected and any articles retrieved in the original search were removed. This process yielded 16,850 novel documents. Assuming that the three-stage screening would be completed at the same rate for the snowballed articles as the main search, the time required to screen and extract meta-data from the snowballed articles was estimated to be 58 weeks. Therefore, completion of snowballing would likely result in the findings from the main search being outdated at the time of publication and the commitment to publish within 2 years of search commencement being breached. Consequently, the decision was taken not to complete the snowballing. Nevertheless, we acknowledge the potential of this technique for finding other relevant literature and encourage interested researchers with the required knowledge to do so.

3.4.2. Search for articles

Databases of commercially published and grey literature were searched in accordance with the published protocol. Two candidate searches were identified that retrieved all articles in a test-list of benchmark articles, and were compared using a title-level screen. The final search was chosen as a balance of search sensitivity and specificity. For full details of the scoping searches that were undertaken in search string development, tests of search comprehensiveness, and how the search string was adapted for each database see the published protocol (Ridley, McGowan and Mair, 2020).

3.4.2.1. Search string

The final search string was as follows. This exact string was used to search SCOPUS and details of how it was adjusted to suit other databases can be found in Appendix B.2.

Search String: (pressure OR threat OR risk OR stress OR footprint) AND (species OR ecosystem OR wildlife OR fauna OR flora OR (spp). OR (sp.)) AND (hotspot* OR map* OR geographic* OR "gis" OR "spatial distribution" OR "spatial overlap" OR "spatial separation" OR "spatial dynamics" OR "spatial variation" OR "spatial framework" OR "spatially explicit" OR geospatial) AND (conservation OR biodiversity)

3.4.2.2. Search limitations

The final search was used to search publication databases, search engines and grey-literature repositories in English for articles published between 2000 and 2020 inclusive. Inclusion of non-English language articles was not considered feasible here due to translation resource restrictions. Furthermore, carrying out snowballing could have retrieved many more relevant articles. Therefore, we openly encourage interested researchers with the necessary skills to repeat our protocol for a non-english language and snowballing searches.

Through further consideration of the eligibility criteria, it was determined that two articles in the original test set of articles did not merit inclusion due to nuances in the definitions of future threats, and mapping (Neke, Du and M, 2004; Bozoki *et al.*, 2018). As these nuances were not detectible in the title, abstract or keywords of the papers, this is not considered to have compromised the comprehensiveness of the search. In addition, having ineligible articles in the test-set may only have resulted in a higher number of irrelevant articles being found rather than limiting the number of relevant articles found. Therefore, the overall impact of this on the comprehensiveness of the systematic map is considered to be minimal.

3.4.2.3. Publication databases

SCOPUS, ProQuest natural Science Collection, and Web of Science Core Collection were searched for published peer-reviewed articles by title, abstract and keywords using the subscriptions of Newcastle University. For specifics of the citation indexes used and how the search terms were adapted for each database please see 'Appendix B.2' or the published protocol (Ridley, McGowan and Mair, 2020).

3.4.2.4. Search engine

Google Scholar was used to identify grey literature by searching the titles with the simplified search string of: (pressure OR threat OR footprint) AND (species OR ecosystem OR wildlife). A title-level search has previously been found more effective than searching the full-text on Google Scholar (Haddaway *et al.*, 2015). The results were ordered by relevance and the first 500 gathered.

3.4.2.5. Grey literature searches

ProQuest Natural Science collection was specifically searched for non-commercially published dissertations and theses, government and official publications, reports, and working papers using the same search string as the ProQuest Natural Science commercially published literature search.

3.4.2.6. Website searches

The following organisational websites were searched for additional grey literature. A bespoke approach was taken that utilised additional search features and repositories within each website. For full details of how each organisational website was searched see Appendix B.2.

- WWF, World Wildlife Fund (WWF, 2020)
- UNEP-WCMC (UNEP-WCMC, 2020)
- Convention on biological Diversity (CBD, 2020b)

- IUCN, International Union for the Conservation of Nature (IUCN, 2020)
- IPBES, Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES, 2020)
- RSPB (RSPB, 2020)
- Fauna and Flora International (Fauna-Flora, 2020)
- The Nature Conservancy (Conservancy, 2020)
- Conservation International (Conservation International, 2020)
- Birdlife International (BirdLife International, 2020)
- Blue Ventures (Ventures, 2020)
- The Audubon Society (Audubon, 2020)
- SCB, Society of Conservation Biology (SCB, 2020)

3.4.3. Search Results

EPPI-Reviewer-Web (Thomas, Brunton and Graziosi, 2010) was used to assimilate and de-duplicate the search results as well as coordinate the screening stage among multiple reviewers. EPPI-Reviewer-Web identifies duplicates based on a similarity algorithm. The threshold for automatic removal of duplicates was set at 0.9, whereby any articles with a similarity score greater than 0.9 were automatically removed. Articles that the duplicate removal tool identified as potential duplicates but had a similarity score of less than 0.9 were checked manually. The application creators advise that duplicates are unlikely to be incorrectly identified above a similarity threshold of 0.8. Therefore, we are confident that no novel articles were incorrectly excluded as duplicates.

To gather the full-text documents of all articles included at the full-text screening stage a combined strategy was used, utilising the Endnote full-text finding tool and manual searching.

3.4.4. Article screening and eligibility criteria

3.4.4.1. Screening process

A three-stage screening process (Title, Abstract, and Full-text) was undertaken using EPPI-reviewer-web (Thomas, Brunton and Graziosi, 2010). At each stage, the articles were compared against the inclusion criteria and a decision made about whether the article was relevant. The following guidance was provided to reviewers about how to manage missing information at each stage.

If there was insufficient information to conclusively exclude a study at title level, articles were included if a potentially relevant human-driven pressure and potentially relevant population were present or alluded to in the title. Terms such as species, ecosystem, and population were considered to sufficiently allude to species and a simultaneous reference to conservation or management was considered to sufficiently allude to a threat. Alternatively, titles that described a relevant human-driven pressure were considered to sufficiently allude to threats, where information on the subject of the pressure was either absent or was not obviously human. Due to the wide variety of titles expected to be retrieved, reviewers were also advised that if they strongly suspected that the study contained the relevant information despite not fitting either of those descriptions, then the study should be reviewed again at abstract level.

At the abstract screening stage, reviewers were advised that where insufficient information was present to confidently exclude a study it should be screened again at full-text level. However, abstracts that were entirely narrative and did not contain any suggestions of primary research, were concluded to be narrative reviews and excluded based on study type.

3.4.4.2. Consistency checking

Two reviewers (FAR and EH) were used to carry out the screening process to test the consistency of study classification. At each screening stage (Title, Abstract, and Full-text) a random 20% of articles were allocated to a second reviewer for double screening via EPPI-reviewer-web (Thomas, Brunton and Graziosi, 2010). Cohen's kappa (Cohen, 1960) was used to compare the proportional agreement between the two reviewers based on two possible coding outcomes: 'Include' and 'Exclude'. At title and abstract level, FAR re-examined all disagreements and, where the reason for disagreement was not obvious (e.g. a clear mistake by either reviewer), the study was included to the subsequent screening stage. At full-text level all disagreements were reconciled by a discussion between the two reviewers. At no point during the screening process were the reviewers involved in decisions regarding the inclusion of their own authored work.

There was weak to moderate agreement between reviewers at the title, abstract, and full-screening stages (Table 3.1, McHugh, 2012). A k value of 0.41 is considered moderate by some authors (Cohen, 1960; Landis and Koch, 1977), meanwhile others have found k to be limited by low numbers of potential coding outcomes and observer accuracy (Bakeman *et al.*, 1997). In particular, it was found that with two coding outcomes the maximum k was 0.8 and could only be achieved with an observer accuracy of 95% (Bakeman *et al.*, 1997). Therefore, given the wide contextual scope of relevant articles and the level of uncertainty associated with the title screening stage, a k greater than 0.5 was deemed acceptable for the title-level screen.

		Exclusion rate (%)			
	n	Reviewer 1	Reviewer 2	Agreement (%)	k
Title	2804	54	59	76	0.51
Abstract	1368	62	73	84	0.64
Full-text	626	66	64	85	0.66

Table 3.1 Results from consistency testing at each stage of the screening process. N indicates the number of articles compared at each stage (20% of the total screened at each stage). K is the measure of inter-rater reliability (Cohen's kappa, Cohen, 1960).

3.4.4.3. Eligibility Criteria

Decisions on whether articles were included or excluded at each stage were made based on the following criteria. For examples of articles that challenged the exclusion criteria and how they were dealt with see Appendix B.3.

3.4.4.3.1. Eligible Population

The taxonomic scope of this study was any wild species of animal or plant globally, in any country or ecological realm (terrestrial, marine, freshwater). Evidence of the presence of individuals or groups of such species was an essential criteria for study inclusion. This included direct observations, remotely sensed observations, modelled distributions, and expert-derived species range maps. Pre-defined priority areas for biodiversity conservation, such as a Biodiversity Hotspot or some protected areas were considered to be valid proxies for species presence. A pre-defined priority area was defined as an area of conservation importance identified in previous work by any author, due to the presence, richness or density of animal or plant species. Examples of acceptable proxies for population presence did not deviate from the protocol and are reiterated in Appendix B.3. Modelled species distributions were only considered sufficient evidence of species presence if data on species presence within the study site were included in the model input. For example, predictions made using solely environmental analogues were deemed insufficient.

Criteria 1A: Excluded if no evidence was given for the presence or distribution of a relevant species within the study area

Criteria 1B: Excluded if the evidence provided was predictively modelled without evidence for species presence at the study site e.g. habitat suitability for the purpose of reintroduction

3.4.4.3.2. Eligible Outcome

The spatial occurrence of threats to species. As defined above, threats occur where species are exposed to threatening human activities and human-initiated processes. Where articles included multiple 'threats' at least one needed to fit the definition used here to qualify for inclusion. If the threat studied was listed on the IUCN classification scheme but was not a result of human action (e.g. geological events) it was excluded. Articles on threats such as fire, extreme weather and disease were only included if they were specifically human-induced within the context of the study. For example, articles of extreme weather were included if they were studied as a consequence of climate-change.

Criteria 2A: Excluded if no data on where species and human-driven pressures co-occur were presented or the 'threat' considered did not fit the definition used here.

Criteria 2B: Excluded if the threat studied was relevant and studied in-situ but the occurrence was not mapped onto a geographic distribution.

Criteria 2C: Excluded if the threat considered was not human-driven.

3.4.4.3.3. Eligible Study Type

Only primary research published 2000–2020 inclusive in English was included, which may use either primary data, or pre-existing datasets. Exceptions could be made in the case of systematic reviews and meta-analyses where data from primary work was collated and re-analysed. Only articles that assessed current threat distributions were included, as opposed to projected future, potential, or historical distributions. Otherwise, all data collection and cartographic methods were included.

Criteria 3A: Excluded if the article was a narrative review in which no new synthesis of data was presented.

Criteria 3B: Excluded if the presented distribution represented a historical, future, or potential distribution of threat to species.

Criteria 3C: Excluded if the spatial context could not be determined (e.g. due to insufficient reporting or schematic presentation), or the threat was not studied in-situ (e.g. theoretical, lab-based, or experimentally applied).

3.4.5. Study Validity Assessment

The validity of individual articles was not assessed beyond study eligibility based on the above criteria, which were written based on the ability of the article to show where species and threatening human activities co-occur geographically. Nevertheless, information on study design and data type was collected for each study allowing for future critical appraisal of the methodology.

3.4.6. Data Coding Strategy

Coding of the articles included at the full-text stage was performed by completing the pre-designed data collection tool which formed the basis of the database, where each study occupied a single row (Appendix B.4). Meta-data were extracted in terms of bibliographic information, study characteristics (study design, ecological realm, spatial scale, spatial resolution, geographic location), threat characteristics (data type, method of collection or synthesis, data source, threats mapped, number of threats mapped, the thematic precision of threats mapped), and population characteristics (data type, method of collection or synthesis, data source, taxonomic resolution, taxonomic scope and taxonomic group). Data were only collected from the main text and supplementary material of each article; there was no subsequent follow up with authors to clarify missing information. A topology with full lists of potential outcomes and examples for each variable coded is provided in the coding tool (Appendix B.4).

3.4.7. Coding threats

Threats were classified according to the IUCN Red List threat classification scheme at the second level of thematic precision in the framework hierarchy, where level 1 was the lowest level in precision and level 3 was the highest. For example, bushmeat harvesting was classed as 'Biological Resource Use' at the first level of precision (level 1) and 'Hunting and Collecting Terrestrial Animals' at level 2. Therefore, for a study that mapped the locations of observed hunting activity, the 'Threat' would be coded as 'Hunting and Collecting Terrestrial Animals' and the 'Threat precision' would be coded as 'Level 2'.

3.4.7.1. Other and unspecified threats

The threat classification scheme was adapted to acknowledge where threats were studied at a precision lower than level 2 or were not captured by the IUCN criteria despite being relevant according to the criteria above. If threats were mapped at level 1 precision without further clarification as to what activities this included, the threat was considered 'unspecified'. For example, if a study mapped agricultural land-use without specifying if the production was timber, non-timber, or livestock, the threat was classed as 'Other or unspecified agriculture and aquaculture' and the threat precision classed as 'level 1'. If the threat satisfied the definition of threats used here but wasn't covered by the IUCN classification, the category 'other' was applied. For example, types of fencing that were not otherwise defined under the IUCN threat classification scheme were classed as 'Other or unspecified linear infrastructure'.

3.4.7.2. Coding consistency

The coding was completed by two reviewers (FAR and EH) to ensure consistency. All included articles were coded by the primary reviewer, and 20% by a second reviewer. Each reviewer independently reviewed all disagreements on coding before the remaining disagreements were discussed and resolved collaboratively. Any necessary clarifications were added to the coding tool.

3.4.8. Data Mapping Method

3.4.8.1. Searchable database

All included articles, coded meta-data and bibliographic information have been made available as an excel workbook (Appendix B.4) and as an online interactive choropleth map https://naturalandenvironmentalscience.shinyapps.io/ThreatMapping_SM/. The interactive choropleth map was constructed using the leaflet (Joe, Bhaskar and Yihui, 2021) and shiny (Chang *et al.*, 2021) packages in R (version 4.1.1, (R Core Team, 2021)). The online interactive map allows users to filter the dataset by any of the meta-data, view the number of articles per country or marine territory, and download a list of citations for their selection.

3.4.8.2. Visual mapping of the meta-data

Summary figures and tables were produced to complement the searchable database and visually map the quantity and quality of evidence relevant to the primary and secondary questions. The taxonomic distribution was visualised using Sankey diagrams that highlighted the relationships among taxonomic group, taxonomic resolution, and taxonomic scope for both animal and plant kingdoms. Co-occurrence matrices were used to identify gaps and clusters in research effort, and observe the linkages between spatial distribution, taxonomy and threats.

To present the geographic distribution of evidence, the geographic location of the study area was collected in data coding. The geographic location was coded either as the country boundary (Belgui, 2015) for terrestrial and freshwater articles or as the marine territory (Flanders Marine Institute, 2019) for marine articles. Where study areas spanned more than one ecological realm, a judgement was made as to which was the most relevant for coding the geographic location.

3.5. Review findings

3.5.1. Review of descriptive statistics

3.5.1.1. Searching and screening

The six peer-reviewed and grey literature databases collectively yielded 29,572 articles. Of these, 15,386 were duplicates and removed, leaving 14,185 articles to be screened (Fig 3.1). In screening, 6,835 (48%) were deemed potentially relevant at title-level, 3,133 (46%) at abstract-level, and 1,046 (33%) at full-text level (Fig. 3.1). 110 full texts were irretrievable whereby the full-text of the article could not be found, or it was inaccessible publicly or via the subscriptions used. Of the 1,977 excluded at full-text level, 22 were originally included at the full-text screening stage but in light of additional information found at the coding stage both reviewers agreed that these articles did not satisfy the eligibility criteria. Combining the 23 articles found through searches of organisational websites resulted in 1,069 threat mapping articles to be included in the final systematic map (Fig 3.1).

Rates of article relevance across the searched sources was low (1.9% - 11.3%, Table 3.2). The source that contributed the highest number of articles to the final systematic map was SCOPUS (881/1069). However, high rates of duplication were recorded for Web of Science Core Collection (WOS) and the search of ProQuest Natural Science Collection for peer-reviewed published articles ($ProQuest_{Pub}$), making the independent ability of WOS and $ProQuest_{Pub}$ to retrieve relevant threat mapping articles uncertain. The search of ProQuest Natural Science Collection for grey literature ($ProQuest_{Grey}$) had the highest rate of relevance in terms of the number of de-duplicated results that were included in the systematic map (Table 3.2).

Source	Date Searched	Total results	Duplicates removed	Relevant full-texts	Relevance rate (%)
SCOPUS	15.9.20	10,646	40	881	8.3
Web of Science Core Collection	15.9.20	8,953	6,544	137	5.7
ProQuest Natural Science (Published)	15.9.20	9,078	8,690	11	2.8
ProQuest Natural Science (Grey Literature)	15.9.20	395	40	26	11.3
Google Scholar	15.9.20	500	72	13	3.0
Organisational Websites	19.4.21 – 27.4.21	1,238	0	23	1.9

Table 3.2. The results of literature searching and duplicate removal, indicating the number of articles from each source that were included after the full-text screening stage. Relevance is the percentage of de-duplicated results that were included after full-text screening. An additional 22 articles were excluded during the coding stage.

At full-text stage most articles were excluded on the outcome component of the eligibility criteria. 986 articles (50% of those excluded at full-text level) investigated the occurrence of threats but did not map the findings. Meanwhile, for 444 articles (23%) the threat studied was found not to meet the definition used here (Fig 3.1). Moderate numbers were excluded due to the lack of a relevant population (159), the study not being a primary synthesis of data (119), or because the study investigated historical, future, or potential threats (186, Fig 3.1). For a full list of articles excluded at full-text level and the criteria that they were excluded on see Appendix B.5.

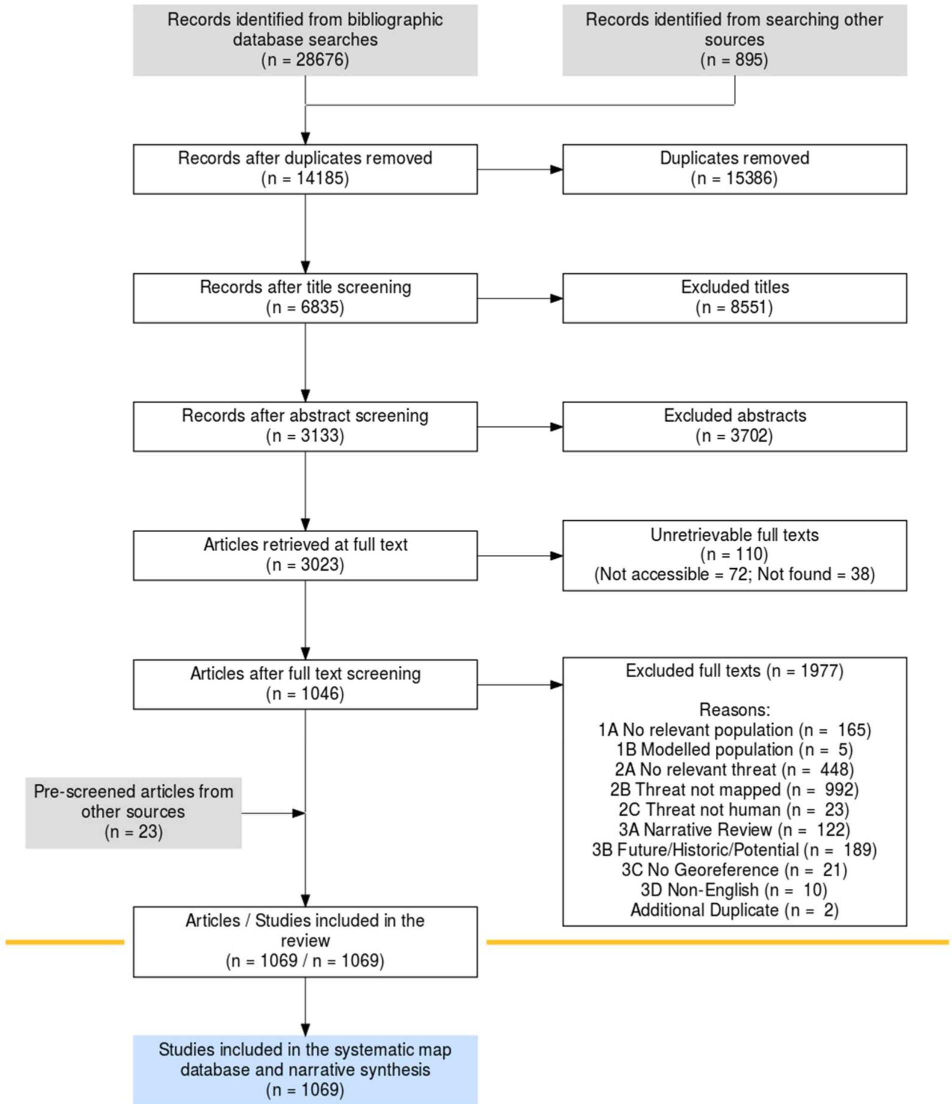

Figure 3.1. The flow of articles through the screening process generated in accordance with the ROSES Reporting standards for systematic evidence synthesis (Haddaway et al., 2018). As all included articles had to present the findings of primary research, all included articles were scientific studies. 'Records identified from searching other sources' refers to articles found in grey literature searching via Google Scholar and ProQuest. 'Pre-screened articles from other sources' indicates the articles found through searching organisational websites.

3.5.1.2. Institutions and article types

The articles included in the final systematic map included 1,011 journal articles, 22 reports, 15 theses, 13 conference proceedings, six dissertations, one book section, and one generic resource. The most common publications were PLOSOne and Biological Conservation (87 and 80 articles respectively), while the remaining 902 articles were split between 302 publications (Table 3.3).

The articles were primarily observational (1,043 articles) with few being systematic reviews (16 articles) or experimental (10 articles). Experimental articles were defined here as any investigation that manipulated variables regardless of tight controls, such as threat exclusion experiments. Qualitative metrics were more commonly used than quantitative metrics to map both the outcome (threats) and the population (600 versus 469 for threat metrics and 754 versus 315 for population metrics).

Publication Name	**Number of Articles**
PLOSONE	87
Biological Conservation	80
Science Of The Total Environment	33
Diversity And Distributions	31
Conservation Biology	29
Biodiversity And Conservation	22
Global Change Biology	22
Journal Of Applied Ecology	20
Ecological Applications	17
Ecological Indicators	17
Ocean And Coastal Management	17
Ecosphere	14
Environmental Management	13
Journal For Nature Conservation	13
Oryx	13
Endangered Species Research	12
Journal Of Environmental Management	12
Environmental Monitoring And Assessment	11
Biological Invasions	10
Proceedings Of The National Academy Of Sciences Of The United States Of America	10
Sustainability(Switzerland)	10
Other	576

Table 3.3. The distribution of articles among publications.

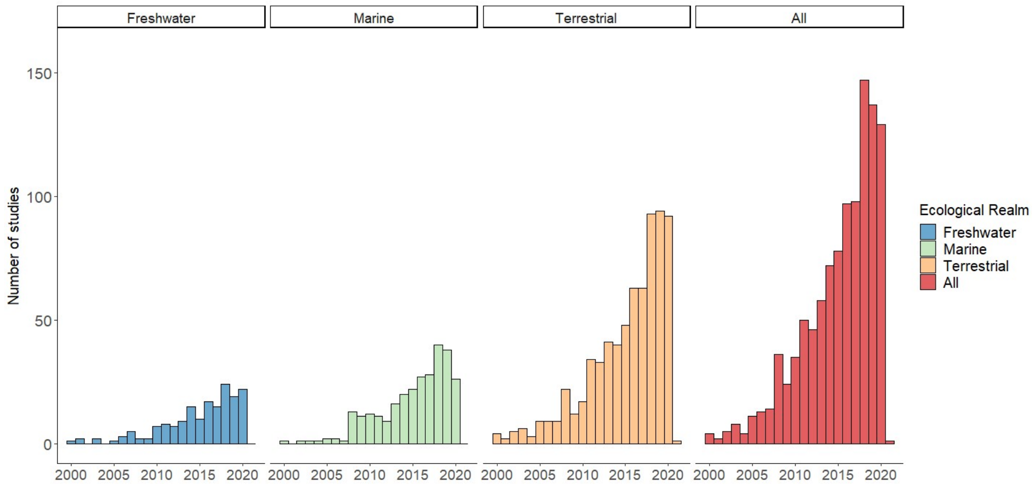

Figure 3.2. The number of threat mapping articles published in each year by ecological realm. Some articles were relevant to more than one ecological realm so the total published in each year is less than the sum of the number published on each ecoregion for that year. Due to the final date of literature searching being 15.9.2020, the data for both 2020 and 2021 were incomplete.

3.5.1.3. Temporal distribution

Of the literature retrieved, the number of threat mapping articles published annually has increased over the last 20 years. Five articles were published per annum across 2000 – 2004. From there, the number of published articles increased annually by 39% on average, to a maximum of 149 articles in 2018 (Fig 3.2). As the main search was completed on the 15th September 2020, both 2020 and 2021 are incomplete.

3.5.1.4. Representation of the major ecological realms

The quantity of threat mapping articles was not distributed evenly among the three major ecological realms. Articles relevant to the terrestrial realm outweighed those studying marine or freshwater environments (700, 282, and 171 respectively). Where articles investigated threats to a system in the boundary between these realms (e.g. estuarine or mangrove species) or covered a wide landscape including multiple of these realms, the codes for all relevant ecological realms were applied. Of these boundary-spanning articles, 47 occupied freshwater and terrestrial zones, 18 marine and terrestrial, 5 freshwater and marine, and 7 were relevant to all three.

3.5.1.5. Distribution among spatial scales

The number of articles generally decreased with increasing spatial scale, with the exception of global-scale articles that were conducted at a similar frequency to national and multi-national scale articles. Overall, 345 articles (32%) were conducted at a local scale (<10,000km^2), 333 (31%) at a sub-national scale (>10,000km^2 within a single country), 123 (12%) at a national scale (an entire country extent, irrespective of area), 124 (12%) at a multi-national scale (>10,000km^2 across multiple countries), 44 (4%) at a continental scale and 100 (9%) at a global scale. Consequently, 75% of all threat mapping articles found were conducted at a national scale or below.

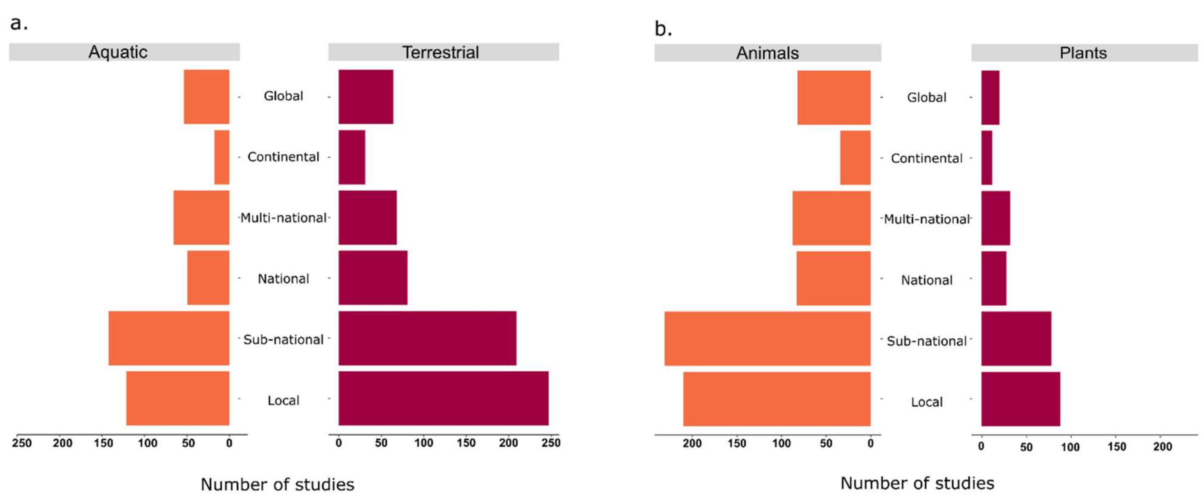

Figure 3.3. The distribution of evidence among spatial scales, compared for expected sources of bias a) Ecological realm b) Taxonomic Kingdom. Some articles covered more than one ecological realm and studied species from more than one Kingdom.

The distribution of articles across spatial scales followed a similar pattern across the compared sub-groups (aquatic versus terrestrial realms and animal versus plant species, Fig 3.3). Almost twice as many articles were conducted on the terrestrial realm as the aquatic realms (marine and freshwater), yet the proportion performed at each spatial scale was approximately similar. Likewise, there were almost three times as many articles on animals as plants, yet the proportions of evidence at each spatial scale were almost identical (Fig 3.3).

3.5.2. Mapping the quantity of articles relevant to the question

3.5.2.1. The geographic distribution of threat mapping literature

Based on the literature retrieved, threat mapping research effort was heterogeneously distributed worldwide. For terrestrial and freshwater threat maps it was found that Asia was represented in the most articles (187) followed by North America (156), Europe (150), Africa (122), South America (110), and Australasia (30). Meanwhile in marine applications, the North Atlantic was represented in 70 articles, the Mediterranean Sea in 48, the North Pacific Ocean in 39, the Arctic Ocean in 9, and the Caspian Sea in 2. While, the South Pacific Ocean (31), Indian Ocean (26), South Atlantic Ocean (14), and South China Sea (8) occurred in 79 articles collectively. Antarctica and the Southern Ocean occurred in 3 marine articles and 1 terrestrial or freshwater study.

The relative proportions of terrestrial and freshwater articles conducted at each spatial scale differed among geographic regions. The preference for local or sub-national-scale threat maps in these two realms was most pronounced for Asia and North America (76% and 87% respectively) and remained present for Europe, Africa, and South America to a lesser extent (61%, 64% and 58% respectively Fig 3.4). Articles of the African continent were more often mapped on a multi-national scale than a sub-national scale (Fig. 3.4). Furthermore, of all articles conducted on a national scale, 29% occurred in Europe (Fig. 3.4).

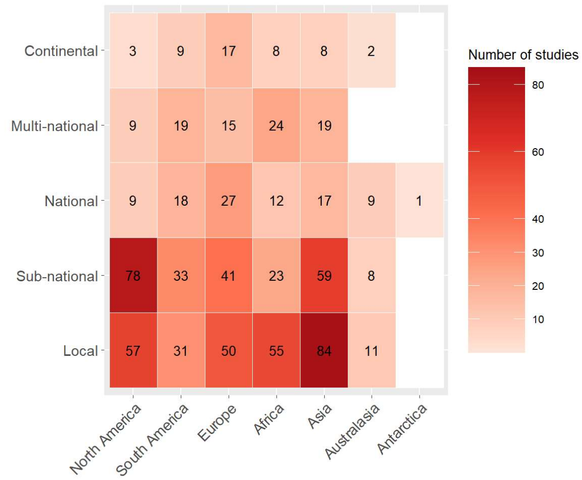

Figure 3.4. The distribution of terrestrial and freshwater articles among continents and spatial scales.

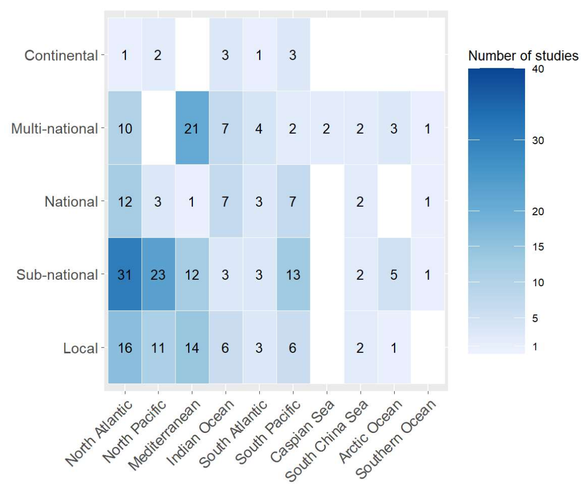

Figure 3.5. The distribution of marine articles among geographic regions and spatial scales.

Threat maps on marine regions were more evenly distributed among spatial scales than terrestrial and freshwater threat maps. Sub-national scale articles formed the highest proportion of those conducted in the North Atlantic (44%), North Pacific (59%), and South Pacific Oceans (42%, Fig 3.5). Meanwhile threats to species in the Mediterranean Sea were more likely to be multi-national (44%, Fig 3.5). Substantive differences among spatial scales were not observed for other marine regions, although overall numbers of articles for these regions were low, making meaningful comparisons difficult.

Threat mapping evidence was found covering 144 countries and 160 marine territories. However, the number of articles per country tended to be low; 50% of countries had five or fewer articles and 107 were absent of evidence. The United States of America was found to be the most heavily studied country (124 articles) and marine territory (36 articles, Fig 3.6). The next most frequently studied countries in the terrestrial or freshwater realms included Brazil (52 articles), China (51 articles), India (48 articles), and Spain (36 articles, Fig 3.6). Therefore, research tended to be clustered around western countries, with some exceptions in large, rapidly-developing countries.

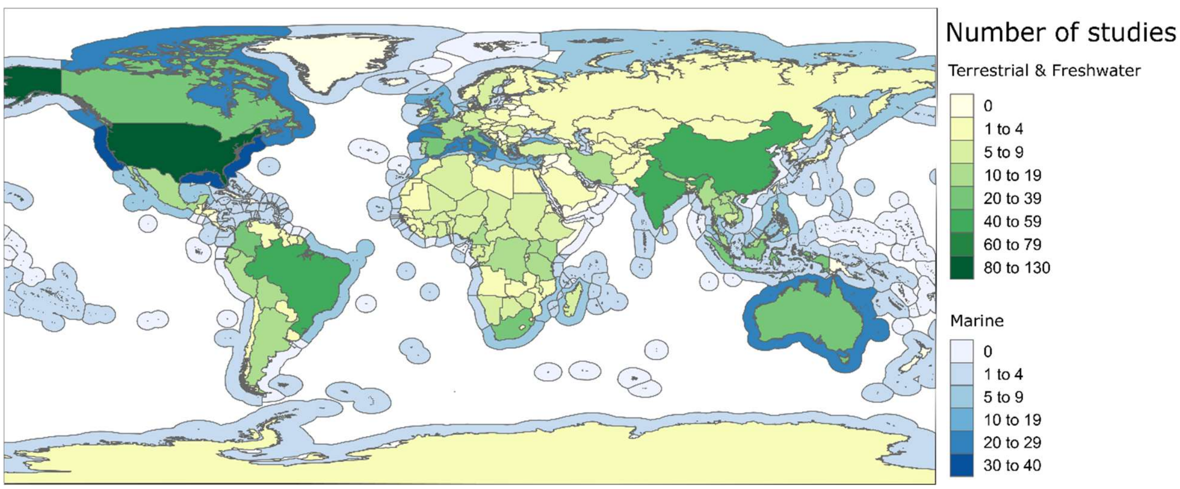

Figure 3.6. The geographic distribution of the 925 threat mapping articles conducted at a multi-national scale or below.

The average number of articles per marine territory was also low, with 50% of marine territories occurring in 2 articles or fewer and 91 marine territories being absent of evidence. The most heavily studied marine territories were the USA (36), Italy (28), Spain (23), Canada (21), Australia (20), and France (20), with the UK and many other Mediterranean marine areas (Greece, Tunisia, Croatia, Morocco, Cyprus, Turkey, Albania, Bosnia and Herzegovina and Slovenia each represented in 10 to 20 articles (Fig 3.6). For a full table of the countries and marine territories mapped and the number of articles representing each, see Appendix B.6.

3.5.2.2. Taxonomic distribution

3.5.2.2.1. Distribution between Kingdoms

Most applications of threat mapping focused on animal species alone (664 articles) with fewer that focused on threats to plant species (193 articles) and 65 articles presented data on both animal and plant species. 147 articles used a valid proxy for species presence, in which 97 mapped threats within a protected area and 57 mapped threats within other high biodiversity areas (Table 3.4).

3.5.2.2.2. Distribution within Kingdoms

Within the animal kingdom, mammals occupied the highest number of articles (287) followed by birds (171), fish (144) and invertebrates (111), while reptiles and amphibians occupied 86 and 70 articles respectively (Table 3.4). 29 articles that mapped threats to animals either grouped species by non-taxonomic characteristics (e.g. extinction risk) or did not specify the taxonomy of the included animal species (Table 3.4).

Of the 258 articles that mapped threats to plants, 181 mapped threats to vascular plants (including forest). 87 articles mapped broad habitat types or unspecified vegetation, 2 articles mapped threats to bryophytes, and 21 mapped threats to other plant species, whereby taxonomy wasn't specified or species were grouped by non-taxonomic characteristics. Furthermore, among vascular plants, forest (77 articles), flowering plants (36), grasses (27), unspecified tracheophytes (27), and mangroves (22) occupied considerably more threat mapping articles than conifers (9) or ferns (2 articles, Table 3.4).

3.5.2.2.3. Taxonomic scope and resolution

In addition to differences in overall research effort between kingdoms, consideration of taxonomic resolution and taxonomic scope revealed differences in the ways that each kingdom was studied. For example, 79% of animal articles mapped species at class-level or below and 49% of contained species-specific threat maps (Fig. 3.7). By comparison, 28% of plant articles mapped threats at class-level or below with 16% that mapped threats at a species-specific level (Fig 3.8). Conversely, threats to plants were more likely to be mapped at a kingdom or domain level (43% and 19% of plant articles respectively) than threats to animals (4% and 7% of animal articles respectively, Fig 3.8). Furthermore, there was a greater proportion of single-species articles among animal threat mapping articles (34%, n = 245) than among plant threat mapping articles (8%, n = 21, Fig 3.7). Therefore the evidence on the spatial occurrence of threats is both more numerous and more taxonomically specific for animals than for plants.

Kingdom	Class	Number of articles
Animal	Mammal	287
	Bird	171
	Fish	144
	Invertebrate	111
	Reptile	86
	Amphibian	70
	Other	29
	Total	**729**
Plant	Magnoliopsida	37
	Liliopsida	27
	Pinopsida	9
	Bryopsida	2
	Polypodiopsida	2
	Other	158
	Total	**258**
Other	Pre-calculated high biodiversity area (PCHBA)	57 (77)
	Protected Areas	97 (160)
	Total	**147**

Table 3.4. The number of articles mapping threats to each taxonomic class. Some articles mapped multiple species from different classes and kingdoms, making the total number of articles for each kingdom different to the sum of the articles for each class. The number of articles that mapped a conservation priority area have been denoted as: the number of articles in which the pre-calculated priority area was used as a proxy for population presence (outside parentheses) followed by the total number of papers in which the priority area was mapped, (i.e. including those where other evidence for population presence were also used, inside parentheses).

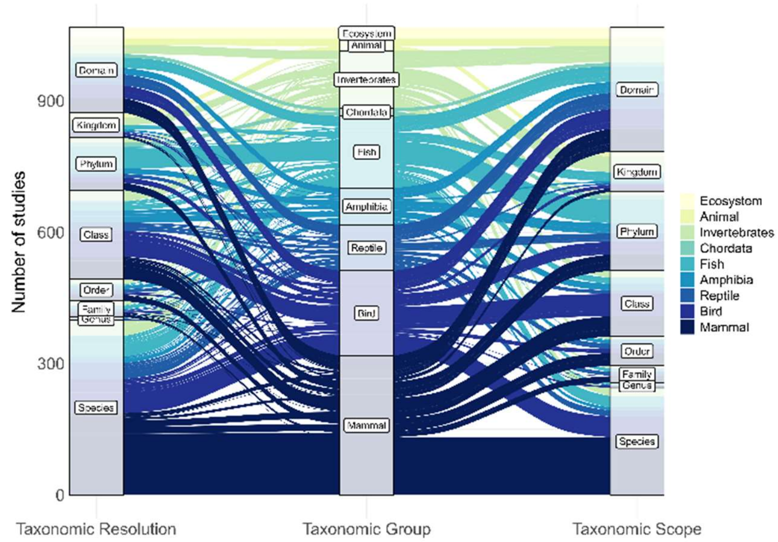

Figure 3.7. The difference in taxonomic resolution and taxonomic scope of retrieved threat mapping literature among animal taxonomic groups. Taxonomic resolution is the lowest taxonomic level that was mapped as an independent population unit, thus indicative of how taxonomically detailed the threat mapping application was. Whereas, taxonomic scope is the lowest taxonomic level that includes all species for which threats were mapped within the article. The width of the flows represents the number of articles.

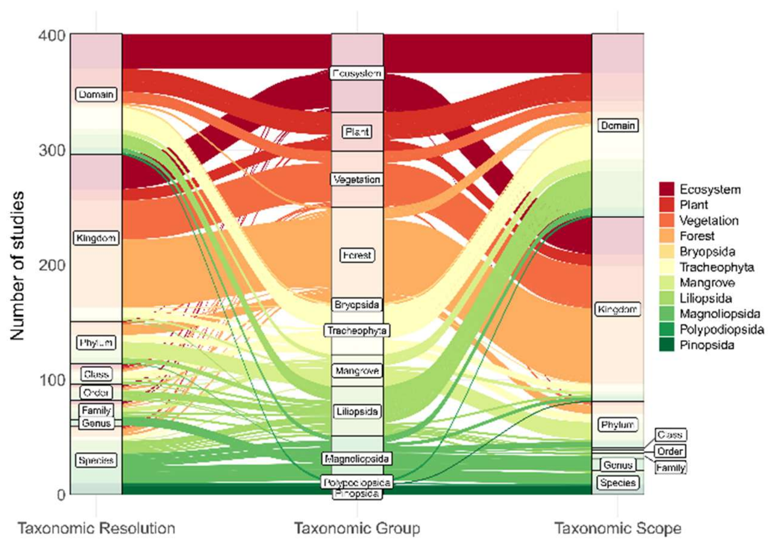

Figure 3.8. The difference in taxonomic resolution and taxonomic scope of retrieved threat mapping literature among plant taxonomic groups. Taxonomic resolution is the lowest taxonomic level that was mapped as an independent population unit, thus indicative of how taxonomically detailed the threat mapping application was. Whereas, taxonomic scope is the lowest taxonomic level that includes all species for which threats were mapped within the article. The width of the flows represents the number of articles.

3.5.2.3. Distribution among threats

Articles were collected that represented all 41 relevant categories of threatening human activities and direct human-initiated processes, in addition to six 'other or unspecified' categories. All articles were classified as examining at least one threat.

Eight threats occurred in 100 or more articles. These were: alien invasive species or diseases (187 articles), fishing and other aquatic resource harvesting (184), roads and railways (172), residential and urban development (170), non-timber crop agriculture (142), unspecified agriculture (114), hunting and collection of terrestrial animals (102), and livestock farming (100, Fig 3.9). Excluding 'other or unspecified' categories, seven threats were mapped in less than ten articles. These were: problematic native species (nine articles), climate-change-induced drought (eight articles), problematic species of unknown origin (five articles), climate-change-induced storms or flooding (four articles), introduced genetic material (four articles), flight paths (two articles), and viral or prion-induced diseases (one study, Fig 3.9).

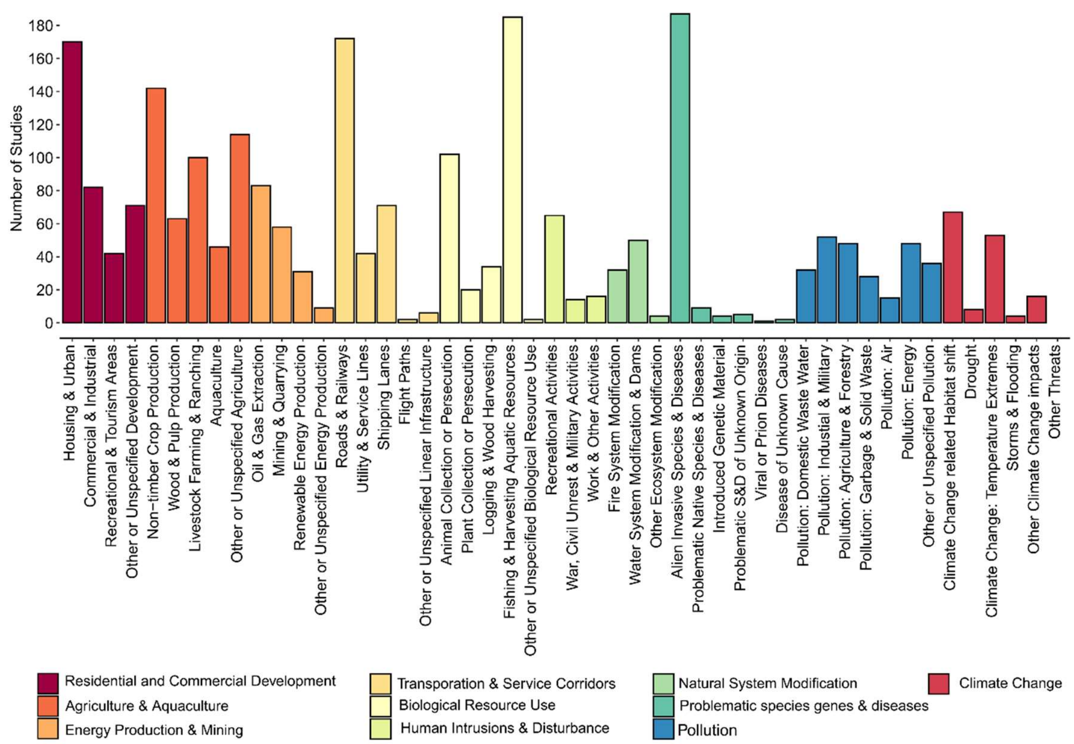

Figure 3.9. The number of threat mapping articles that mapped each threat. Threats were classified according to the IUCN threat classification scheme (Salafsky et al., 2008). Colours indicate groups of thematically similar threats (i.e level 1 in the threat classification scheme).

When threats were grouped thematically, ‘Agriculture and aquaculture’ was overall the most frequently mapped threat group (323 articles), followed by ‘Biological resource exploitation’ (314 articles), ‘Residential and commercial development’ (280 articles), and ‘Transport and utility lines’ (268 articles, Fig 3.9). ‘Problematic species’, ‘Pollution’, ‘Energy and mining’, and ‘Climate change’ each occupied between 101 and 204 articles. Meanwhile, two threat groups featured in less than 100 articles, which were: ‘Human intrusion and disturbance’ (87) and ‘Natural system modification’ (81, Fig 3.9).

3.5.2.3.1. Terrestrial

The distribution of research effort among threats differed somewhat with geographic location, though three threats (alien invasive species, roads and railways, and residential development) were widely studied across the terrestrial realm (Fig 3.10). Roads and railways occupied 10-29% of articles on the Asian, Australasian, European, North American, and South American continents. Meanwhile, Alien invasive species occupied 50% of articles in Australasia, 23% of articles in North America, 21% of articles in Europe, and 8-14% of articles in Asia, South America, and Africa. Furthermore, Residential development varied widely, from 11% in Australia to 27% in Africa (Fig 3.10).

When threat groups were considered collectively, agricultural threats were also widespread, although of greater importance in the global south. Articles mapping agricultural threats for Asia, Africa, and South America, collectively occupied 46%, 51%, and 42% of all terrestrial threat maps on these continents respectively. This was much larger than in Europe, North America, and Australia for which agricultural threats represented 20 – 25% of the total threat mapping articles on each continent.

There were some differences in terrestrial threats among continents. Europe contained a relatively high proportion of articles mapping recreational disturbance (10%) and renewable energy production (12%) in comparison to the other continents (Fig 3.10). Whereas, animal resource exploitation was mapped at an above average rate for Africa, South America, and Asia (28%, 18%, and 13% respectively, Fig 3.10). Four threats were mapped in the single study of terrestrial Antarctica, these were residential development, recreational development, recreational disturbance, and work & other disturbance.

3.5.2.3.2. Freshwater

32 threats were mapped in the freshwater realm, eleven of which were mapped on two continents or fewer (Fig 3.11). Alien invasive species was the most ubiquitously mapped freshwater threat, being the most heavily mapped on Australasia (75% of articles), Europe (51%), North America (39%) and Africa (32%, Fig 3.11). Alien invasive species was also the only freshwater threat for which threat mapping articles were found on all continents. 'Water system modification and damming' was also reasonably widespread, ranging from 14-31% of threat mapping articles on each continent and was mapped on every continent apart from Australasia (Fig 3.11).

3.5.2.3.3. Marine

Threat mapping articles were found for 38 of 47 threats in the marine realm, with 13 threats mapped on two continents or fewer. Fishing and aquatic resource harvesting was mapped across all marine regions, ranging from 50% to 100% of articles on each marine region (Fig 3.12). Study of shipping lanes was similarly widespread; only absent from the Caspian Sea. However, the contribution to the overall body of threat mapping literature found in each region was lower (12-44%, Fig. 3.12). Oil and Gas extraction, aquaculture, and commercial development were also studied with above average frequency across most marine regions (Fig. 3.12). Furthermore, some form of pollution was mapped for every marine region and, when considered collectively, represented 11-47% of articles on each marine region (Fig. 3.12).

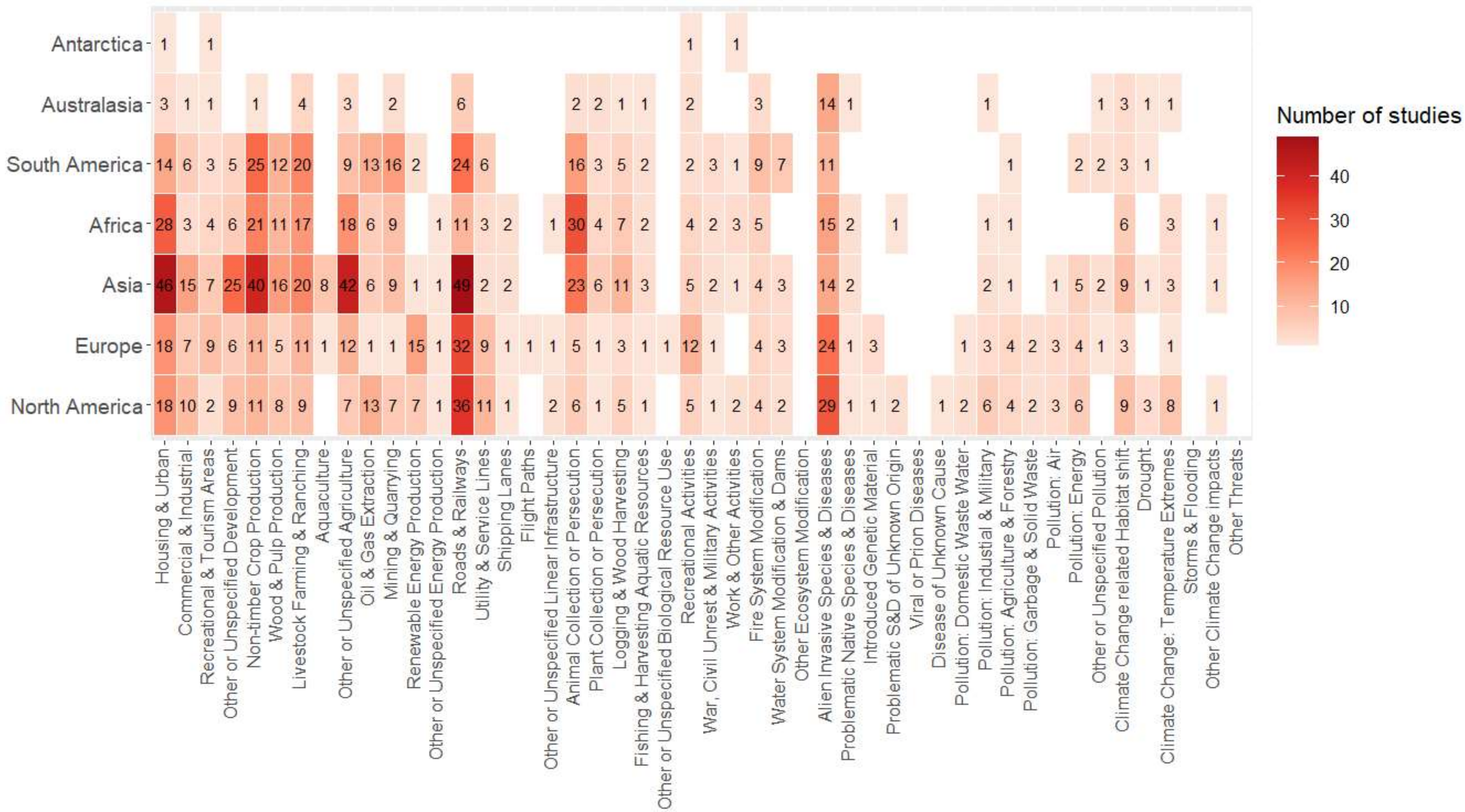

Figure 3.10. The representation of different threats in the terrestrial threat mapping literature and differences among geographic regions.

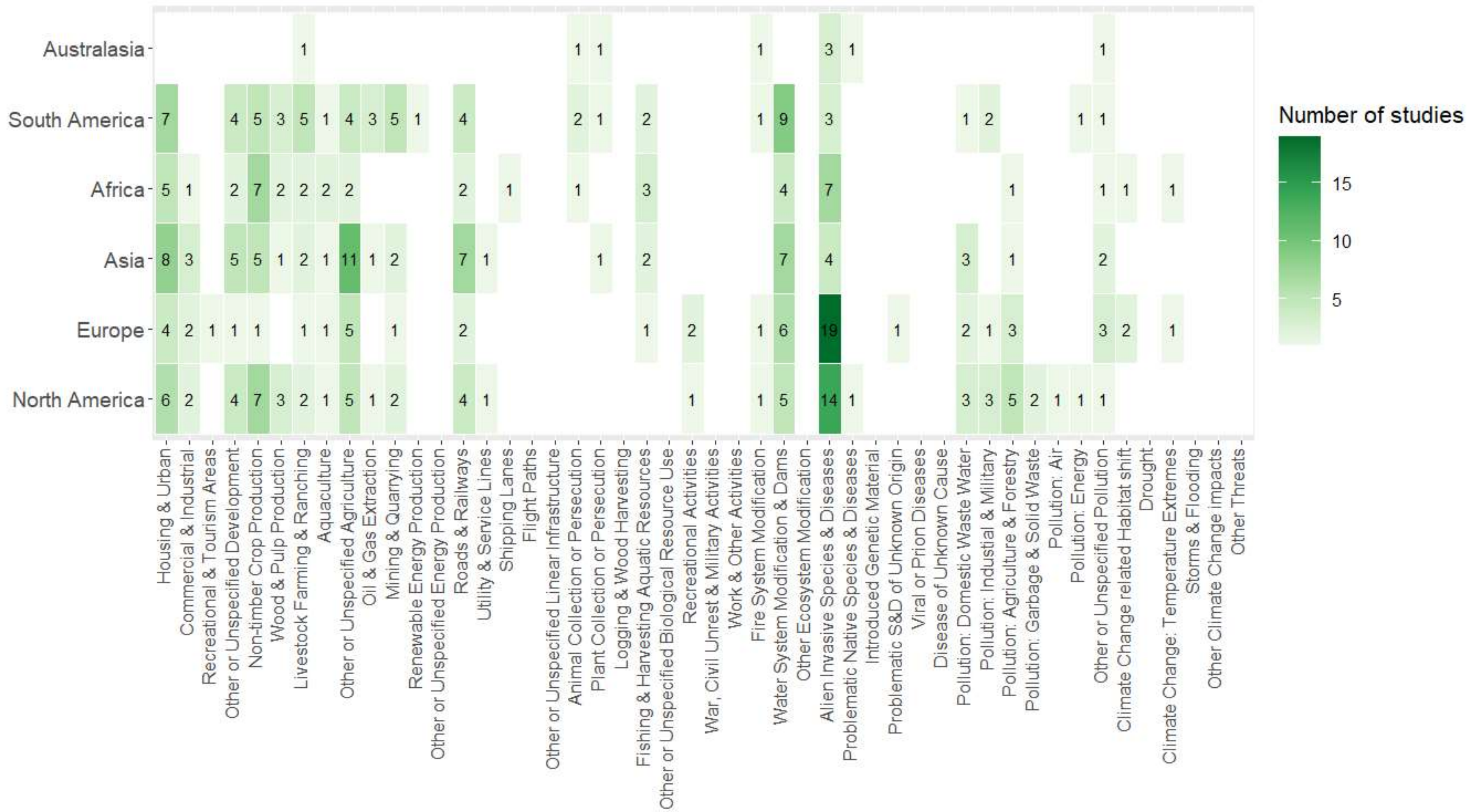

Figure 3.11. The representation of different threats in the freshwater threat mapping literature and differences among geographic regions.

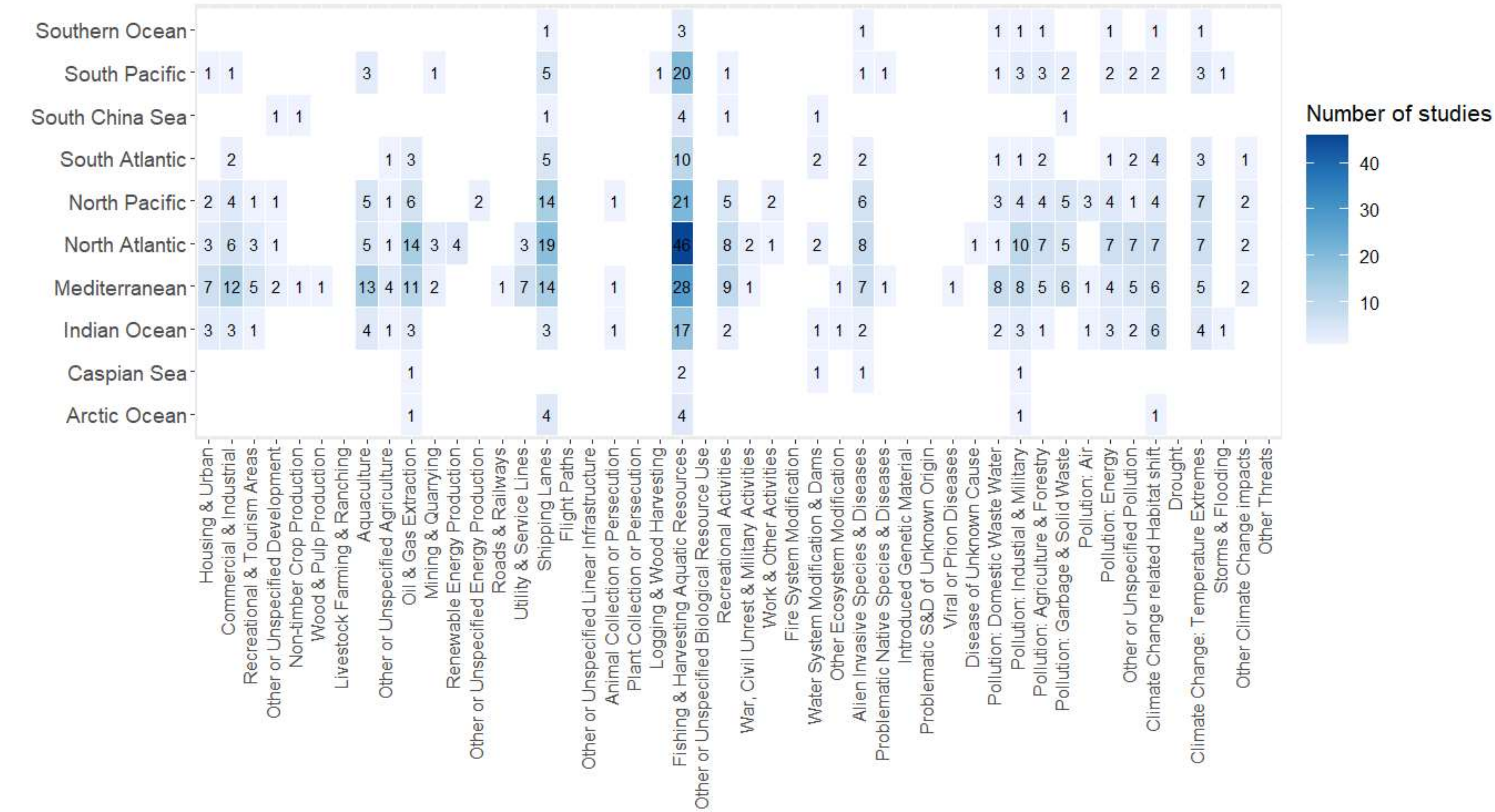

Figure 3.12. The representation of different threats in the marine threat mapping literature and differences among geographic regions

3.5.2.4. The number of threats considered in each study

Threats tended to be mapped in isolation. 60% of threat mapping articles mapped a single threat, whilst 91% of articles mapped five or fewer (Fig. 3.13). Most threats were mapped at the most precise level (862 at level 2, e.g. Residential an Urban Development), and fewer were mapped cumulatively (different threats combined into one index, 136 articles) or at level 1 (71, e.g. Residential and Commercial Development). Threat precision decreased as the number of threats per study increased (Fig. 3.13). For example, 96% of articles that mapped one threat did so at level 2 precision. Whereas, 74% of articles mapping ten or more threats and all articles mapping 14 or more threats, did so cumulatively (Fig. 3.13). Therefore, most evidence is contained within single-threat articles and thematic precision tended to be lost as the number of threats increased.

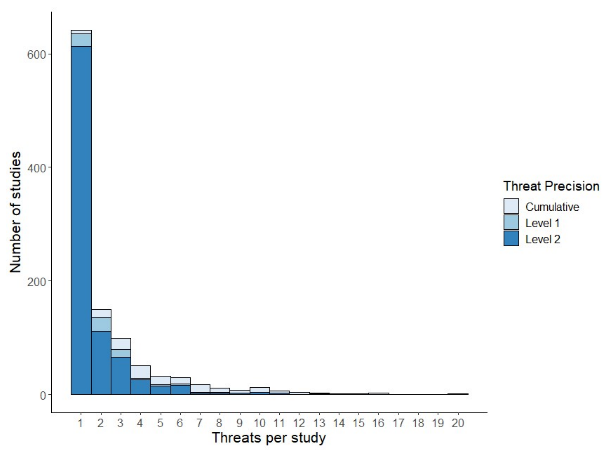

Figure 3.13. The number of different threats mapped within each threat mapping study, indicating the thematic precision at which threats were mapped. 'level 2' is the finest level of precision (e.g. Oil and Gas Drilling), 'level 1' (e.g. Energy production and mining) is less precise, and 'cumulative' indicates where multiple thematically different threats were mapped as one.

3.5.3. Mapping the quality of articles relevant to the question

3.5.3.1. The methods used to map the spatial occurrence of threats to species

A range of methods were employed to map the threats to species, with many articles using more than one method. 23% of articles used multiple methods to map threats and 16% used multiple methods to map the population. Overall, ground-level survey methods were the most frequently-used source of data used to map the population (used in 32% of articles), followed by existing databases (24%), remote sensing (16%), and sourcing from the existing literature (15%, Table 3.5). Meanwhile, existing databases were the most frequent source of data on threats (used in 31% of articles), followed by ground-level survey methods (27%), remote sensing (22%), and sourcing from the existing literature (15%, Table 3.5). Far fewer articles utilised expert elicitation methods to map the population (5%) or threat (7%). Furthermore, modelling techniques were more commonly utilised to map the threat (21%) than the population (11%, Table 3.5). Finally, a small number of articles were found that used a pre-calculated metric of threats (2%) in comparison to 22% of articles that used a protected area or pre-calculated high biodiversity area to map the population (Table 3.5).

Some of the methods used to map the spatial occurrence of threats to species did not fit within the classification used. Nine articles used other methods to map threats and five used other methods to map the population (eleven collectively). Of these, five used social media and other online platforms (Sonricker *et al.*, 2012; Abreo *et al.*, 2019; Hausmann *et al.*, 2019; Jensen *et al.*, 2019; Liu, Song and Deng, 2019), three used museum or other archives (Lawler, White and Master, 2003; Kraus *et al.*, 2012; de Castro *et al.*, 2017), and for three articles it was unclear how the locations of the mapped threats were determined (Montevecchi *et al.*, 2012; Kitzes and Shirley, 2016; Tancell, Sutherland and Phillips, 2016, Table 3.6).

		Number of Articles using each method/data source for each question component	
Type	**Method**	**Population**	**Outcome (Threat)**
Primary Collection	Survey	346	292
	Expert Elicitation	49	75
	Remote Sensing	172	237
Secondary Collection	Database	261	330
	Literature	164	160
Primary Synthesis	Modelled	119	221
Secondary Synthesis	Pre-calculated Metric (or PCHBA)	77	17
	Protected Area	160	-
	Other	5	9

Table 3.5. The methods used to map the spatial occurrence of threats to species. PCHBA = pre-calculated high biodiversity area (e.g. Biodiversity Hotspots Myers et al., 2000 or Key Biodiversity Areas IUCN, 2016).

Study	Other method: Population	Other method: Outcome	Description
(Abreo *et al.*, 2019)	X	X	Social Media
(Hausmann *et al.*, 2019)		X	Social Media
(Jensen *et al.*, 2019)	X	X	Social Media and online trading platforms
(Kitzes and Shirley, 2016)		X	Unclear how the locations of the dams were determined
(Kraus *et al.*, 2012)		X	Museum specimens (in combination with other methods)
(Lin *et al.*, 2019)		X	Social Media
(Montevecchi *et al.*, 2012)		X	Unclear how the locations of the oil slick or the extent of oil coverage were determined
(Sonricker *et al.*, 2012)	X	X	Social Media and online news
(Tancell, Sutherland and Phillips, 2016)		X	Unclear how the locations of different marine resource-use designations were determined
(de Castro *et al.*, 2017)	X		Museum records (in combination with other methods)
(Lawler *et al.*, 2003)	X		Natural Heritage records (in combination with other methods)

Table 3.6. Descriptions of the methods used in the eleven articles where the method of mapping either the population or outcome component could not be classified under the framework used.

Population Data Sources	Number of Articles	Threat Data Sources	Number of Articles
IUCN	53	Government Data	45
Government Data	17	IUCN	15
BirdLife	12	FAO	10
GBIF	6	Land Cover/Land Use	10
FishBase	5	Human Footprint	9
Nature Serve	5	Marine Impact (Halpern)	8
Aquamaps	2	WorldClim	7
Biodiversity Hotspots	2	GBIF	5
NOAA	2	Climate Research Unit	3
Other	125	Other	246
Source not found	57	Source not found	32

Table 3.7. Databases recorded from articles where the population data were gathered from an existing database and the threat data used were either a pre-calculated metric of threat or gathered from an existing database. 'Source not found' indicates that although the paper used existing data, neither reviewer found information on the source of the data.

3.5.3.2. Datasets used to map threats to species

Across the 408 articles that used data from existing databases to map either the population or threats, 142 population databases and 291 threat databases were used. Databases were recorded as reported in the articles, therefore some of the underlying datasets may overlap (e.g. IUCN Red List and BirdLife). IUCN Red List and government sources of data were the most common sources for both population and threat data (Table 3.7). Furthermore, the source population database was not identified in 57 articles and the source threat database was not identified in 32 articles (Table 3.7).

3.5.4. Limitations of the map

3.5.4.1. Search strategy

The search strategy included two databases and 13 organisational websites specifically designed to target grey literature, yet journal articles were the primary document type among articles included in the review. Given this systematic map was global in scope, we chose to search the websites of organisations that operate internationally. It is possible that smaller-scale organisations involved with conservation planning and management could contain additional applications of threat mapping. Contacting the organisations directly may have also been a more successful method of identifying novel unpublished research applications than online repositories. Therefore, an organisational website search targeting smaller organisations directly could result in further applications of threat mapping being found.

As previously identified above, language also represents a limitation of the search strategy. The contextual and linguistic nuances associated with this investigation presented significant challenges and thus reinforced the decision only to include articles published in English. However, we recognise that this presents a risk of overlooking articles from non-English speaking countries. Therefore, we openly invite researchers with sufficient language resources to replicate this analysis for threat mapping research published in non-English languages. Regardless, it should be acknowledged that the English-only search and imperfect ability to target organisational resources could have contributed to the uneven distribution of literature observed.

3.5.4.2. Eligibility Criteria

The multi-faceted and diverse nature of the retrieved literature meant that a large number of articles conceptually challenged the eligibility criteria. For example, NDVI was not considered a valid proxy for wild species presence as it alone cannot distinguish between natural and human vegetation (Khorram *et al.*, 2016). However, NDVI was considered a valid method for measuring the extent of threats such as logging where other evidence was provided to confirm the eligibility of the population and threat. Nonetheless, levels of consistency still met the proposed threshold for the abstract and full-text screening stage. Challenging articles were discussed when the review team met to consolidate disagreements and efforts were made to update the coding tool. However these nuances were not always generalisable to changes in the eligibility criteria. Therefore, a list was kept of recurring examples of such articles and how they related to the eligibility criteria (Appendix B.3).

This systematic map was limited to articles that presented visually the geographic distribution of threats, therefore it does not represent an exhaustive collection of all the articles on in-situ threats that exist. For example, fifty percent of articles excluded at the full-text screening stage studied an otherwise relevant population and threat but either did not study it spatially or did not visually present the geographic distribution of these two components. Therefore, more evidence on the spatial distribution of threats to species could be generated by gleaning the country or study-site location from any study investigating the effect of a relevant threat on populations of animals or plants.

Furthermore, consistency among reviewers at the title-screening stage was slightly lower than desired. All reasonable efforts were made to minimise the impact of this on the review findings within the time available, such as reviewing all disagreements again at abstract level. However, it is possible that some relevant articles were excluded at this stage.

3.6. Conclusions

This systematic map collected and consolidated literature that mapped the threats to animal or plant species across the world. The number of threat mapping articles has increased through time from five articles published in 2000 to a maximum of 149 in 2018.

The final database consists of 1,069 articles, covering all 41 relevant IUCN threat categories and an additional six 'other or unspecified' categories. Of these articles, most studied a single threat. Therefore, the systematic map cannot necessarily provide information on the relative impact of particular threats on species in selected areas, but it can be used as a starting point for detailed syntheses of the available evidence and an organised repository of relevant information for use in threat reduction and spatial planning for conservation.

Evidence was distributed unevenly among every study attribute we assessed: spatial scales, geographic locations, ecological realms, taxonomies, and threats. The freshwater realm was the subject of substantially less research effort than the terrestrial and marine realms. Global threat maps were disproportionately numerous in all ecological realms, while the more focussed articles tended to be conducted at a sub-national or local scale in the land or sea territories of developed nations in the global north (particularly the USA). In terms of target species, animals, particularly mammals, birds, and fish, received greater research attention in comparison to other taxonomic groups, with non-vascular plants, reptiles, and amphibians receiving less attention. Similarly, some threats were more frequently studied (alien invasive species, harvesting aquatic resources, roads and railways, and residential development), whilst, other threats were seldom studied (non-alien invasive species, genes or diseases, climate-change-induced drought, storms or flooding, and flight paths).

3.6.1. Implications for policy/management

3.6.1.1. Implications for the Post-2020 Global Biodiversity Framework

This systematic map found generous amounts of threat mapping evidence of direct relevance to the post-2020 Global Biodiversity Framework (IPBES, 2019b; CBD, 2021). In particular, maps of agriculture and aquaculture, alien invasive species, and residential development were in relatively high abundance. This evidence could be synthesised or used directly to inform biodiversity-inclusive spatial planning.

The high abundance of articles mapping the threat of roads and railways indicates that specific acknowledgement of this threat under the post-2020 framework might be beneficial to preventing species extinctions. The evidence for various impacts of roads on species is extensive (Alexander and Waters, 2000; Liu *et al.*, 2008; Barthelmess, 2014; Boulanger, Stenhouse and Margalida, 2014; Espinosa, Celis and Branch, 2018; Haider *et al.*, 2018; Schuler and Relyea, 2018; Zingraff-Hamed *et al.*, 2018; Kantola *et al.*, 2019; Liu *et al.*, 2019; Krief *et al.*, 2020; Pinto, Clevenger and Grilo, 2020; Silva, Crane and Savini, 2020; Grilo *et al.*, 2021), though efforts to reduce the direct threat of transport infrastructure are challenged by the critical role of transport in economic and social development (Ghebreyesus, 2017; Hine *et al.*, 2019; Asher and Novosad, 2020). Furthermore, a 60% increase in global road and rail network length is expected by 2050 (Dulac, 2013). Therefore, there is reason to consider the benefits to biodiversity of specifically targeting roads and railways under the post-2020 framework.

Biological resource use has been identified as the most pervasive threat to species (Maxwell *et al.*, 2016) and is specifically featured in the Post-2020 framework. Threat mapping evidence found on it was heterogeneously distributed and clustered around terrestrial Asia, Africa, and South America, where there is higher reliance of communities on wild meats for sustenance, and presence of illicit wildlife trades (Davies, 2002; Davies and Brown, 2008; Nasi *et al.*, 2008). Nonetheless, hunting and persecution of animals also occurs in Europe and North America (Cade, 2007; Pain, Fisher and Thomas, 2009; Quevedo *et al.*, 2017; Madden, Rozhon and Dwyer, 2019; Liberg *et al.*, 2020; Burnside, Pamment and Collins, 2021) where mapping evidence for this threat was limited. Therefore, this systematic map will be useful for the implementation of targets on terrestrial biological resource use in Asia, Africa, and South America but more evidence is needed elsewhere. Furthermore, here biological resource use in the terrestrial and marine realms does not distinguish between intentional and unintentional effects (e.g. bycatch), which each require different methods of threat reduction (McClellan *et al.*, 2009; Dunn, Boustany and Halpin, 2011; Barz *et al.*, 2020). Therefore, further targeted synthesis of articles that map the threat of biological resource exploitation could have large benefits for threat reduction activities on land and marine spatial planning.

3.6.1.2. Implications for national and local policy/management

Decision-makers at a local and national scale will be able to use the database of articles to quickly and easily identify evidence of relevance to their specific application. Further critical appraisal and extraction of the magnitude of threats for each study are necessary to translate the evidence into threat reduction activities. Therefore, the systematic map and corresponding database of articles presents a valuable starting point for evidence-based decision-making for threat reduction at local and national scales.

3.6.2. Implications for research

This systematic map has reinforced the need to fill knowledge gaps in the previously identified areas of bias (taxonomy, geography, and ecological realm). In particular, plants and freshwater systems were starkly under-studied. Research effort in these areas was not only low overall, but low in particular foci expected to be of high conservation need. For example, articles of biological resource use on plants and in the freshwater realm were scarce, despite 42% of threatened plant species and 41% of threatened freshwater species (animals and plants) being threatened by biological resource use (IUCN, 2022). Our findings also agree with others that there are geographic biases towards North America and Europe and against Africa and areas of South America and Asia (Donaldson *et al.*, 2016; Hughes *et al.*, 2021; Rocha-Ortega, Rodriguez and Córdoba-Aguilar, 2021). The above gaps are widely acknowledged but efforts to fill them continue to be hampered; we add our voices to those who call for more research into these underrepresented regions, countries, continents, taxa and ecological realms, which are equally threatened by human activities.

The disproportionately high number of global maps we found will feed into a wider debate on the purpose of global conservation priority mapping (Wyborn and Evans, 2021). We found almost as many global-scale threat maps as threat maps of any other spatial scale for either Africa or South America. Global scale analyses overlook contextual specificities and complexities in decision-making that influence the success of conservation interventions (Hulme, 2010; Waylen *et al.*, 2010; Turnhout and Boonman-Berson, 2011; Evans *et al.*, 2017). Meanwhile, actions to implement global frameworks like the Post-2020 Global Biodiversity Framework occur at a national level, yet a scarcity of maps has been reported in national strategies for both climate change and biodiversity (Cadena, 2019; Schmidt-Traub, 2021). Therefore, we encourage researchers and individuals responsible for conducting global assessments to explore synthesising the collective findings from smaller-scale threat maps before conducting a global-scale map, and to prioritise filling knowledge gaps at the national level, where implementation is most likely to occur.

Specific knowledge gaps were observed in land-based threats to marine systems and in the simultaneous study of multiple threats. There is an extensive body of literature to support the importance of land-based threats to the marine realm (Windom, 1992; Williams, 1996; Brodie, 2002; Halpern *et al.*, 2009b; Brown *et al.*, 2019; Loiseau *et al.*, 2021; Raha, Kumar and Sarkar, 2021) and the importance of managing multiple threats (Bolten *et al.*, 2011; Auerbach, Tulloch and Possingham, 2014; Beyer *et al.*, 2018; Tulloch, Chadès and Lindenmayer, 2018; Dudgeon, 2019; Geary *et al.*, 2019; López-Mendilaharsu *et al.*, 2020). However, we found that most articles investigated single threats and few threat-mapping articles of the marine realm investigated land-based threats, representing critical gaps in knowledge. Therefore, specific research that maps the land-based threats to the marine realm, and the spatial interactions between different threats, could have large benefits for conservation outcomes.

This systematic map of the literature details the uneven distribution of retrieved threat mapping literature across threats, taxonomies, geographies, and methodologies. It highlights clusters in knowledge of relevance to the implementation of the Post-2020 Global Biodiversity Framework and draws attention to knowledge gaps that may distort our understanding of where and how human activities threaten species to inform future research. Moreover, the interactive database of threat mapping literature provides a user-friendly tool that makes this area of research more accessible to conservation policy-makers and practitioners.

Chapter 4: Global mismatches in threat mapping research effort and the potential of threat abatement actions to reduce extinction risk

4.1. Abstract

Targeted actions to abate (reduce and mitigate) the direct threats to species are required to curb the ongoing global extinction crisis, for which threat mapping is a valuable tool. There are known gaps in the threat mapping literature for particular threats and geographic locations, however it is unclear if the distribution of research effort is appropriately targeted relative to conservation need. Here, we aim to understand the drivers of research effort and to quantitatively identify gaps, which if filled, could inform actions with the highest potential to reduce species' extinction risk. We used a negative binomial generalised linear model to analyse research effort as a function of threat abatement potential (quantified as the potential reduction in species extinction risk from abating threats), species richness, land area, and human pressure. We found that more threat mapping research was performed on country-threat combinations with higher threat abatement potential, however species richness and land area were stronger predictors of research effort. For 75% of country-threat combinations there was no observed mismatch between research effort and threat abatement potential. Of particular urgency is filling the knowledge gap on the threat of Agriculture, Aquaculture and Biological Resource Use across the tropical regions of the Americas, Asia, and Madagascar. Conversely, in many North American and European countries, the threat of Linear Infrastructure, and the threat of Biological Resource Use specifically in sub-Saharan Africa, all received disproportionately high research effort. We discuss potential methodological and socio-political reasons behind the gaps and biases found, and urge the need to redistribute conservation effort more effectively among threats and geographic locations.

4.2. Introduction

Transformative change is needed to curb the ongoing loss of global biodiversity and achieve the Convention on Biological Diversity's 2050 goal of 'Living in harmony with nature' (CBD, 2021; Leadley *et al.*, 2022). There is growing evidence that multi-faceted strategies including protection, threat abatement (reduction and mitigation), and managed recovery are essential to achieve positive outcomes for the state of biodiversity (Bolam *et al.*, 2022; Leadley *et al.*, 2022). As effective recovery actions largely rely on the abatement (reduction and mitigation) of direct threats (Hutchings *et al.*, 2012; Crees *et al.*, 2016), and large portions of land, ecosystems, and species are already subject to intense human pressure (Jones *et al.*, 2018; Brondizio *et al.*, 2019; O'Bryan *et al.*, 2020), threat abatement is a critical feature in the global strategy to combat biodiversity loss (CBD, 2022c).

Threat maps are a type of conservation priority map that have intuitive potential to inform threat abatement action planning. Here, a threat map is defined as a visual presentation of the geographic occurrence of threats, whereby threats are considered to occur where human activities and direct human-initiated process (i.e. pressures) co-occur with, and negatively impact, individuals or populations of wild species. The utility of conservation priority maps generally has been demonstrated at a variety of scales: to prioritise physical and financial resources (Myers *et al.*, 2000; CEPF, 2020; Tulloch *et al.*, 2020), to generate public and policy awareness (Brooks *et al.*, 2006; Carwardine *et al.*, 2012; Wyborn and Evans, 2021), and to inform systematic conservation plans (Margules and Pressey, 2000; Auerbach, Tulloch and Possingham, 2014; Tulloch et al., 2015). However, critical analysis of the utility and extent of use of threat maps has so far been limited.

Undetected gaps and bias in an evidence base can result in inaccurate generalisations or predictions leading to ill-informed conservation decisions and inefficient resource use (Trimble and van Aarde, 2012; Hughes *et al.*, 2021). Selection bias (hereafter simply 'bias') occurs when research effort is not distributed evenly, or is not representative, of equally relevant study subjects (Delgado-Rodriguez and Llorca, 2004). Bias in conservation has been studied extensively for a variety of applications including species observations (Hughes *et al.*, 2021), listing procedures for recovery planning (Walsh *et al.*, 2013), ex-situ conservation methods (e.g. gene banks, Al Beyrouthy *et al.*, 2019), reintroduction projects (Seddon, Soorae and Launay, 2005), effectiveness of conservation actions (Christie *et al.*, 2020) and overall conservation research effort (Darwall *et al.*, 2011; de Lima, Bird and Barlow, 2011; Brooke *et al.*, 2014; Donaldson *et al.*, 2016; Fleming and Bateman, 2016; dos Santos *et al.*, 2020). Commonalities among the findings of these studies include a tendency to study charismatic terrestrial vertebrates (Darwall *et al.*, 2011; Walsh *et al.*, 2013; Donaldson *et al.*, 2016; de Barros *et al.*, 2020) with larger body sizes (Brooke *et al.*, 2014; Tensen, 2018; dos

Santos *et al.*, 2020) and more temperate geographic regions, particularly in North America and Europe (de Lima, Bird and Barlow, 2011; Christie *et al.*, 2021; Hughes *et al.*, 2021; Ridley *et al.*, 2022). Further, most studies did not find a relationship between species studied and extinction risk (Seddon, Soorae and Launay, 2005; Brooke *et al.*, 2014; Tensen, 2018). The distribution of research effort on drivers of biodiversity loss have been found not to reflect policy priorities (Mazor *et al.*, 2018) and while there is a high frequency of studies into habitat-change-related threats (agriculture and aquaculture, and residential or commercial development) and alien invasive species, there are comparatively few studies on the threat of pollution (Ridley *et al.*, 2022).

Any deviation from need-driven research effort arguably represents an inefficient use of limited resources, yet practicalities often outweigh conservation-need in decisions over study design. There is a well-evidenced bias towards study sites that are easily accessible to humans (de Lima, Bird and Barlow, 2011; Mair and Ruete, 2016; Monsarrat, Boshoff and Kerley, 2019; Hughes *et al.*, 2021), while countries with a greater per capita GDP and human development index tend to have greater capacities to support research (Fisher *et al.*, 2011; Giam and Wilcove, 2012; Reboredo Segovia, Romano and Armsworth, 2020). It is also acknowledged that individual researchers, institutions and funders may have subjective or regionally-specific motivations for choosing particular locations or topics that do not undermine the validity of the individual studies (Taylor *et al.*, 2015). Regardless, understanding bias leads to more accurate interpretations of the existing evidence and promotes more effective targeting of future research effort, particularly where urgent global challenges are involved.

Most studies that investigate bias in conservation science infer the presence of bias based on the distribution of research effort alone (Walsh *et al.*, 2013; Brooke *et al.*, 2014; Hughes *et al.*, 2021) rather than attempting to measure or quantify conservation need (e.g. extinction risk, de Lima, Bird and Barlow, 2011). For example, Ridley *et al.* (2022) highlighted large differences in the distribution of threat mapping research effort among different threats. However, without data on conservation need, it cannot be determined whether any observed lack of research represents a bias or an appropriate allocation of resources.

This study aims to relate existing threat mapping effort to species' conservation need, in order to identify what further research would be most beneficial to reducing species' threats and extinction risk. To do this, threat mapping research effort was modelled against conservation need for terrestrial mammals and birds across combinations of 204 countries and 11 threats. I used the species threat abatement and restoration (STAR, Mair *et al.*, 2021) metric as a measure of conservation need as it quantifies the contribution that actions to abate particular threats in particular locations can make to reducing global species extinction risk (hereafter threat abatement potential).

Our analysis sought to answer the following questions: 1) Is there a relationship between research effort and conservation need when other needs-based and socioeconomic drivers of research effort are accounted for? 2) Which of the needs-based and geopolitical drivers has the greatest relative effect on research effort? and 3) For which geographic areas and threats is there a mismatch in threat mapping research effort relative to threat abatement potential? Finally, I discuss the extent to which current research diverges from a needs-driven knowledge-production system, highlighting countries and threats of high international priority for research attention, funding, and/or on-the-ground action.

4.3. Materials and Methods

4.3.1. Quantifying threat mapping research effort

Threat mapping research effort was quantified per threat per country as the number of studies (published 2000 – 2020 inclusive) in which the geographic occurrence of threats to species was mapped geographically. Studies mapping threats to mammals and birds only were used due to the sparsity of studies on other taxa and to limit variation among taxa.

Data on threat mapping research effort were obtained from a systematic map of the threat mapping literature by Ridley *et al.* (2022). Following a systematic searching and screening process, the study authors identified 1,069 unique threat mapping studies and classified them according to 22 methodological and thematic attributes (Ridley *et al.*, 2022). Of these, 707 studies mapped threats to terrestrial or freshwater bird or mammal species at a multi-national scale, national, or local-scale and were included here (multi-national scale was defined by Ridley et al. (Ridley *et al.*, 2022) as a study extent over 10,000km^2 across multiple country boundaries but that did not cover over two thirds of any continent). Numbers of studies were summed across each unique combination of country and threat. I adopted a national-scale resolution due to the availability of data quantifying the hypothesised socio-economic predictors of research effort at this scale (see 4.1.3 below) and this is the scale at which much policy-setting and conservation planning takes place (CBD, 2006; ten Brink *et al.*, 2014; Gov.uk, 2022). All countries or territories for simplicity are herein referred to as countries and named according to (Belgui, 2015).

Threats were considered at the first level in the hierarchical IUCN threat classification Salafsky *et al.* (2008). I excluded 'Geological Events', which are not a human activity or a direct human-initiated process. As such the eleven threats considered here were: Residential & Commercial Development (Development), Agriculture & Aquaculture (Agriculture), Energy Production & Mining (Energy & Mining), Transportation & Service Corridors (Linear Infrastructure), Biological Resource Use (i.e direct exploitation), Human Intrusion & Disturbance, Natural Systems Modifications, Invasive and other problematic species, Pollution, Climate Change (including extreme weather), and Other Threats. Other Threats, in both IUCN red list assessments and in applying the classification scheme to threat mapping studies, was used to indicate a threat (potentially new or emerging) that did not fit into any of the other categories (Salafsky *et al.*, 2008; Ridley *et al.*, 2022).

4.3.2. Quantifying threat abatement potential

Data on threat abatement potential ($STAR_T$) was extracted from the species threat abatement and restoration (STAR) metric developed by Mair *et al.* (2021). Full details are provided in (Mair *et al.*, 2021), but in brief, the $STAR_T$ scores for country i and threat t were calculated as:

$$T_{t,i} = \sum_{s}^{N_s} P_{s,i} W_s C_{s,t}$$

(Eqn 1 (Mair *et al.*, 2021)

where $P_{s,i}$ is the current area of habitat (AOH, (Brooks *et al.*, 2019) of each species s within location i (expressed as a percentage of the global species' current AOH), W_s is weighting of species s based on its IUCN Red List extinction risk category (Near Threatened = 1, Vulnerable = 2, Endangered = 3, Critically Endangered = 4, Butchart *et al.*, 2004; Butchart *et* *al.*, 2007), $C_{s,t}$ is the relative contribution of threat t (Salafsky *et al.*, 2008) to the extinction risk of species s, and N_s is the total number of species in country i. $STAR_T$ values for each threat to Near Threatened or Threatened mammal or bird species in each country were summed across species to get the $STAR_T$ score per country per threat.

4.3.3. Quantifying relative research effort

In order to identify country-threat combinations that were relatively under-studied and those receiving high relative research effort, we calculated a novel Relative Research Effort (RRE) metric. RRE was calculated as the scaled difference between the number of studies and threat abatement potential (STAR) for each country-threat combination. Both the number of studies and threat abatement potential (STAR) were rescaled to a 0 to 100 scale to compare their levels relative to each other and the range of potential values for each variable as follows:

(Eqn. 2 (Olivoto and Lúcio, 2020))
$$Rv_i = \frac{100}{Omax - Omi} * (O_i - Omax) + 100$$

(Eqn. 3)
$$RRE_i = R(Studies_i) - R(STAR_i)$$

Where Rv_i is the rescaled value of the variable (studies or STAR) for the ith country-threat combination, *Omax* and *Omin* are the original maximum and minimum values of the variable, and O_i is the original value of the variable for the ith country-threat combination. RRE_i is the difference between the rescaled number of studies and rescaled STAR for the ith country-threat combination, indicating research effort relative to threat abatement potential and total research effort.

A negative *RRE* indicates country-threat combinations receiving low relative research effort and positive values indicate country-threat combinations receiving high relative research effort. RRE does not account for expected differences in research effort due to country size or species richness. RRE values -1 to 1 were considered to tend to zero (relatively balanced), values -25 to -1 indicated country-threat combinations that were moderately understudied, values -50 to -25 were strongly understudied, and values -100 to -50 were severely understudied. Meanwhile, values 1 to 25 were considered to indicate country-threat combinations receiving moderately high relative research effort, 25 to 50 indicated high relative research effort, and 50 to 100 indicated very high relative research effort.

4.3.4. Modelling the drivers of research effort

4.3.4.1. Data on other needs-based and socioeconomic drivers of research effort

Needs-based and socioeconomic covariates were selected based on their potential to influence conservation priority or research effort and national availability at a global scale. These included land area (World Bank), human population (World Bank), Gross Domestic Product (GDP, USD, World Bank), Human Development Index (HDI, UNDP), mammal and bird species richness (IUCN Red List, 2022), road density (Meijer *et al.*, 2018), and the Human Footprint Index (HFI, Venter *et al.*, 2018). Road density was calculated as the length of any main, secondary, tertiary, or local road (m) per square kilometre of land. For seven countries (Federated states of Micronesia, Greenland, Guernsey, Jersey, Kiribati, Pitcairn Islands, and Svalbard & Jan Mayen), vector files of all roads were downloaded from DIVA-GIS and lengths calculated in ArcMap. Finally, extant mammal and bird species richness was calculated using data from the IUCN Red List of Threatened Species (IUCN Red List, 2022). Country data were downloaded from the IUCN Red List website (IUCN Red List, 2022) for all extant mammal and bird species. Species of all origins that have not been confirmed as extinct post-1500 were counted per country.

HFI Venter *et al.* (2018) was used to estimate the proportion of each country's land area that was under intense human pressure. Raster imagery of the human footprint index (1km x 1km resolution) was used to calculate the proportion of area within each country for which HFI was greater than or equal to three. The human footprint index is an established metric of human pressure and has been shown to correlate with species extinction risk (Di Marco *et al.*, 2018). A human footprint of three is considered to be where threats such as agricultural land uses and roads become prevalent in the landscape (O'Bryan *et al.*, 2020), and has previously been used to study the exposure of species (Di Marco *et al.*, 2018) and protected areas (Jones *et al.*, 2018) to human pressure.

4.3.4.2. Missing data

For the small proportion of countries covariate data were unavailable using the above sources (3-12% for each variable). For these, data were gathered via manual searching (details in Appendix C.1). Manual searching failed to find data on GDP for 9 countries (Christmas Island, French Guiana, Martinique, Mayotte, Niue, Reunion, Western Sahara, Pitcairn Islands, and Svalbard & Jan Mayen) so these countries were excluded from the analysis. Data on HDI were unavailable for 34 countries but these countries were not excluded. Since HDI was collinear with GDP (Pearson's r = 0.66), HDI was removed from the final model (see section 4.3.4.3 below), and as such the removal of countries missing HDI data was not necessary.

4.3.4.3. Hypothesised model of threat mapping research effort

Generalised linear mixed effect models were used to investigate the relationship between the number of threat mapping studies and the country-level covariates. The number of threat mapping studies as a response variable was non-normal, in that the data were over-dispersed and studies were clustered. Models were therefore fitted with a negative binomial error distribution. A nested random effect were used to account for unmeasured variation arising from threat within countries. All predictors were standardised by dividing the difference between each value for the variable and the variable mean by the variable standard deviation. The data was further explored for zero-inflation, collinearity, and relationships among covariates. As a result, human development index (correlated with per capita GDP) and human population density (correlated with road density) were removed as predictors. The full model predicted the number of threat mapping studies to be a function of land area (km^2), threat abatement potential (STAR), GDP per capita (GDP), road density (m/km^2), IUCN Red-listed mammal and bird species richness, and proportion of land area subject to intense human pressure.

4.3.4.4. Model selection

The final model was determined using a backwards stepwise model selection strategy in which each of the covariates were removed and the Akaike's Information Criterion (AIC) compared among the models with different excluded parameters and with the model retaining all covariates (the full model). This process was repeated until no further removal of covariates could improve the fit of the model by Δ2 AIC. If dropping a parameter resulted in a decrease in AIC of less than 2, the model with the fewest parameters was retained.

4.3.4.5. Model evaluation

The final model was validated by simulating new data from the fitted model and examining the distribution of scaled residuals using the 'DHARMa' package in R (Hartig and Hartig, 2017), following other applications of similar models e.g. (Smith *et al.*, 2022). The distribution of the residuals were examined visually relative to all included and excluded covariates and among countries. Despite the large proportion of country-threat combinations for which zero studies were found (82% of country-threat combinations), 72% of 1000 simulated datasets predicted the proportion of zeros to be higher than the proportion observed. Therefore, no adjustments to the model to account for zero-inflation were necessary (Zuur *et al.*, 2009). For full details of model validation see Appendix C.2.

The percentage of explained variation (pseudo-R^2) was estimated by trigamma approximation using the 'MuMln' package in R (version 1.46.0, Barton, 2020) as the model utilised a log link function. Incident Risk Ratios (IRRs) with 95% confidence intervals were used to evaluate the relative effect sizes of each of the predictors and were calculated as the exponential of each parameter estimate. As the input data were standardised, IRRs represent the change in the response per standardised unit change in each predictor (Wiley and Wiley, 2019). All data management and analyses were performed in R (version 4.2.1) and models were built using the package 'lme4' (Bates *et al.*, 2014).

4.4. Results

I found that Biological Resource Use was overall the most studied threat, occurring in 171 studies across all countries (24% of 707 studies), followed by Transportation and Service lines (hereafter 'Linear Infrastructure', 146 studies, 23%). The United States had the greatest number of studies of any country (79, 11% of studies), followed by Canada (30, 4%). Italy, Australia, China, Brazil, Indonesia, and Spain had more than twenty studies. The highest number of threat mapping studies published 2000 – 2020 for any country-threat combination was for Linear Infrastructure in the United States (20 studies, Fig. 4.1). 1,893 (81% of 2,244) country-threat combinations had no threat mapping studies, and for 90 of 204 countries no threat mapping studies were found.

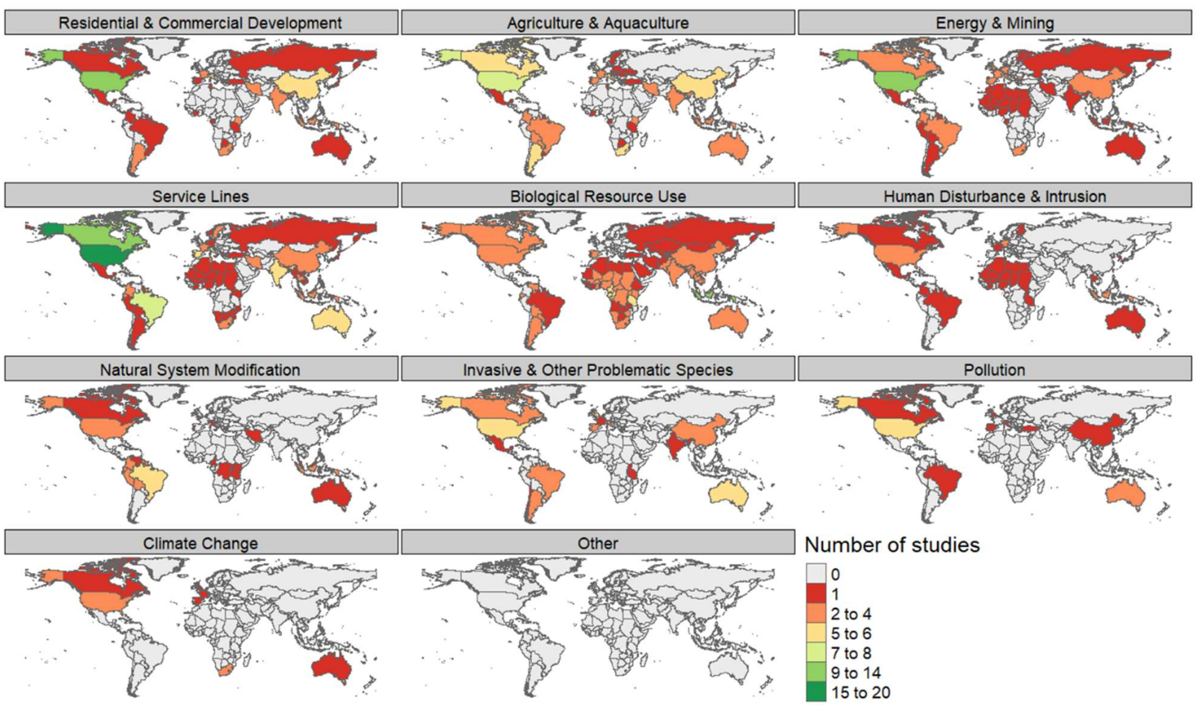

Figure. 4.1. Number of threat mapping studies per threat per country. Studies were conducted on threats to terrestrial mammal or bird species at a multi-national scale or below. Data was extracted from Ridley et al. (2022) where multi-national was defined as a mapped area of over 10,000km^2 that includes the territory of multiple countries whilst covering less than 2/3 of any one continent.

4.4.1. The distribution of relative research effort

The relative research effort of 1,680 unique country-threat combinations (75%) was balanced (-1 < x < 1). 233 combinations (10%) were moderately understudied, eight (0.4%) were strongly understudied and seven (0.3%) were severely understudied. 304 received moderately high research effort (13.5%), nine received high research effort (0.4%), and three (0.1%) received very high relative research effort (Fig. 4.2).

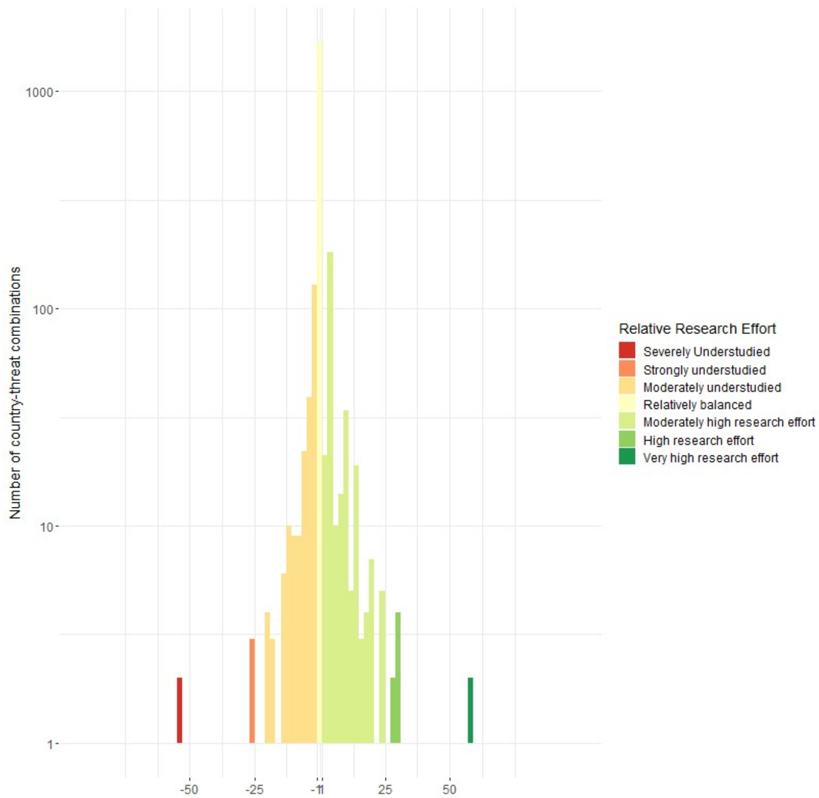

Figure. 4.2. The distribution of relative research effort among unique combinations of country and threat.

Severely understudied country-threat combinations were: Colombia, Madagascar, Peru, Ecuador, Brazil, Indonesia, and Mexico all for the threat of Agriculture (in order of descending relative research effort, Fig. 4.3). Strongly understudied combinations consisted of the threat of biological resource use in Mexico, Madagascar, Indonesia, Colombia, Brazil, and the Philippines, and Agriculture in India and Venezuela (Fig. 4.4). All threats were represented among the moderately understudied country-threat combinations. Most of which were for the threat of Agriculture (44 country-threats, 19% of all combinations) which combined with Invasive and other problematic species (39, 17%) and Climate Change (36, 15%) collectively represented over half of the moderately understudied country-threat combinations (figSX). Some 75 countries were represented among moderately understudied country-threat combinations, primarily those in Central and South America (66, 28%) and small-island states (60, 26%), with African and Asian countries also making up relatively large proportions (22% and 19% respectively).

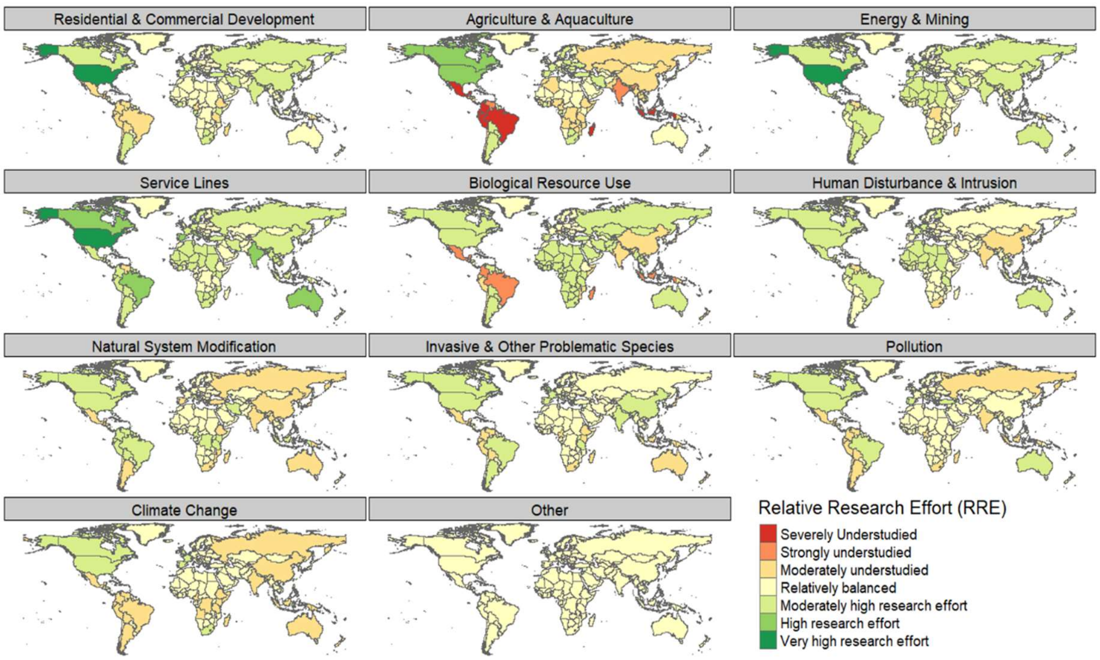

Figure. 4.3. Relative research effort for each combination of country and threat.

Three country-threat combinations received very high relative research effort. These were Linear Infrastructure, Development, and Energy in the United States. A further nine country-threat combinations had high relative research effort: Linear Infrastructure in Canada, Italy, Spain, Brazil, Australia, and India, Agriculture in the United States and Canada, and Invasive and Other Problematic species in the United Kingdom. All threats apart from ‘Other Threats’ were represented among those receiving moderately high research effort. Biological Resource Use received moderately high relative research effort for the highest number of countries (n = 71, 23%), followed by Linear Infrastructure (n = 56, 18%, Appendix C.3).

4.4.2. The drivers of threat mapping research effort

The results of the model indicated that the number of threat mapping studies for any country-threat combination increased with increasing mammal and bird species richness ($z = 7.16$, $p < 0.001$), land area ($z = 2.67$, $p = 0.008$, Table 4.1), and to a lesser extent, threat abatement potential ($z = 3.55$, $p < 0.001$, Fig. 4.4). The extent of intense human pressure (% land area) did not significantly predict the number of threat mapping studies ($z = -1.95$, $p = 0.051$, Table. 4.1), albeit marginally so, and its exclusion reduced model fit. The combination of fixed and random effects explained 23.6% of the variation in number of threat mapping studies. Incident Rate Ratios (IRRs) indicated that species richness had the greatest effect on threat mapping research effort followed by land area and STAR to a lesser extent.

Parameter	Estimate (± s.e)	IRR (95% CI)	z-value	p-value
Intercept	-2.84 (± 0.14)	0.1 (0.0 – 0.1)	-19.95	<0.001
STAR	0.13 (± 0.04)	1.1 (1.1 - 1.2)	3.55	<0.001
Species Richness	0.79 (± 0.11)	2.2 (1.8 – 2.7)	7.16	<0.001
Land Area (km2)	0.25 (± 0.09)	1.3 (1.1 – 1.6)	2.67	0.008
Extent of intense human pressure (% of land area)	-0.21 (± 0.11)	0.8 (0.7 – 1.0)	-1.95	0.051

Table. 4.1. Parameter estimates from the final model predicting threat mapping research effort with estimated Incidence Rate Ratios (IRRs) and 95% confidence intervals. The generalised linear model was fitted on a negative binomial distribution with a random intercept that varied with country and threat. All predictors were standardised prior to modelling by dividing the difference between each value for the variable and the variable mean by the variable standard deviation. σstudies =1.10

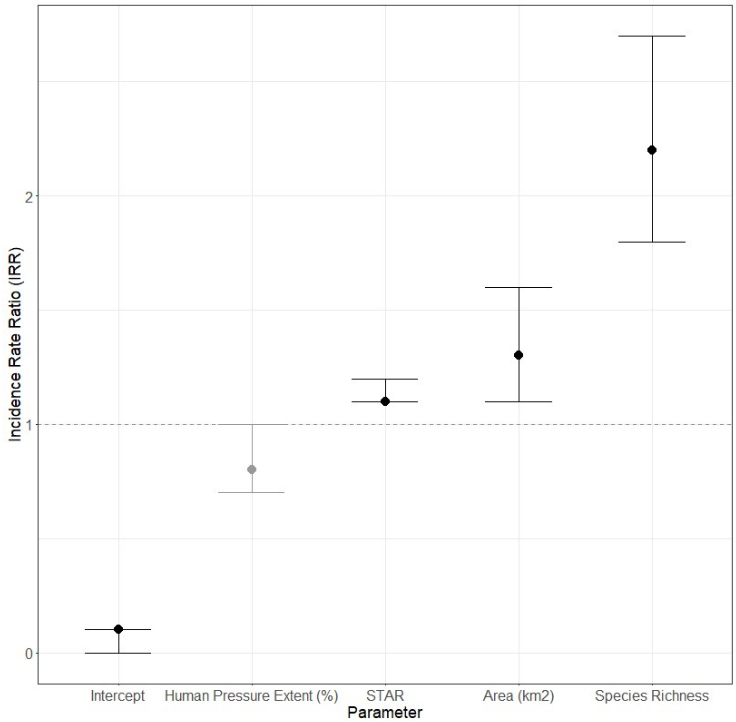

Figure. 4.4. Incidence Rate Ratios (± 95% confidence intervals) from the negative binomial generalised linear model predicting the number of threat mapping studies for each unique combination of country and threat. Non-significant parameters are displayed in grey.

Approximately one-quarter of the variation explained by the model was provided by the nested random intercept of threat and country (marginal R^2= 0.081, conditional R^2= 0.236). The variance was similar between the random intercept of *country* (d^2 = 1.15, s.d = 1.035) and *country:threat* (d^2 = 1.24, s.d = 1.056), though the latter explained more variation than the former (conditional R^2 = 0.128).

The random intercept revealed that 21 countries were the subject of larger numbers of studies than average when the effects of area and species richness were accounted for (Appendix C.3), In descending order: Italy, Spain, France, United Kingdom, Portugal, Tunisia, Iran, South Africa, Equatorial Guinea, Lebanon, Germany, Nepal, Turkey, Burkina Faso, United States, Greece, Rwanda, Canada, Malaysia, Suriname, and Australia) and eight countries were on average the subject of fewer numbers of studies (In descending order: China, Ecuador, Indonesia, Colombia, Venezuela, Russia, Brazil, Peru). Of the 94 country-threat combinations that were the subject of above average numbers of studies, the largest proportion (36%) were on the threat of Biological Resource Use (predominantly in African countries) followed by Linear Infrastructure (21%, fig5). Of the six country-threat combinations subject to below average numbers of studies three were Agriculture (Colombia, Ecuador, and Brazil), one was Natural System Modification (China), and two were 'Other threats' (the United States and Canada, fig5).

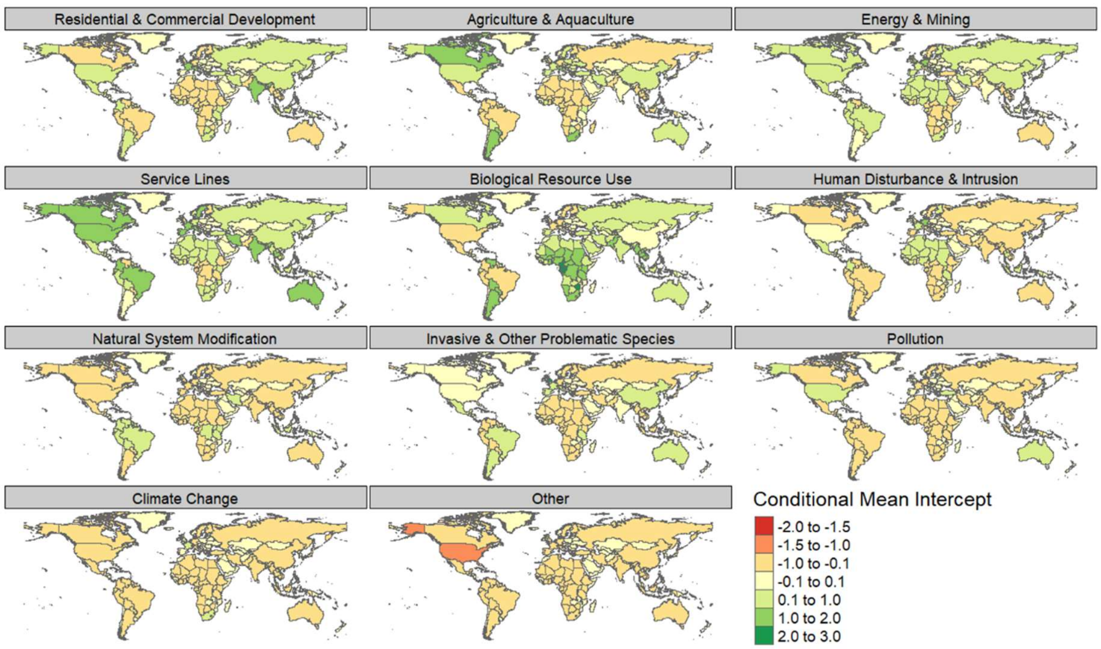

Figure. 4.5. Random intercept of threat nested in country from the negative binomial generalised linear model. Negative values indicate country-threat combinations that had fewer studies than expected after the effects of land area and species richness were accounted for.

4.5. Discussion

This investigation is the first to quantitatively model selection bias in the threat mapping literature and highlight gaps in knowledge of high value to the implementation of threat abatement actions. I found that in general research effort and conservation need were balanced, but these results highlight an urgent need for knowledge on the spatial distribution of the threat from Agriculture in tropical regions of the Americas, Asia, and Madagascar. Meanwhile, countries in North America and Europe, Biological Resource Use in Sub-Saharan Africa, and Linear Infrastructure ubiquitously, received high relative research effort. We also found that countries in North America and Europe are overall the subject of more threat mapping studies relative to threat abatement potential, reflecting wider patterns of bias in conservation science (de Lima, Bird and Barlow, 2011; Christie *et al.*, 2021; Hughes *et al.*, 2021).

4.5.1. Mismatches receiving high research effort relative to conservation need

However, the bias towards Biological Resource Use and Linear Infrastructure is unexpected, especially given the divergence in observability and spatial context between these two threats. Linear Infrastructure can be studied with relative ease as it overcomes the documented barrier of accessibility (Reddy and Dávalos, 2003; Mair and Ruete, 2016; Monsarrat, Boshoff and Kerley, 2019) either intrinsically (roads and railways) or via maintenance infrastructure (utility lines). Whereas, biological resource use does not have a permanent observable footprint and datasets on it are less readily available making this threat more challenging to study and map (Joppa *et al.*, 2016). Linear Infrastructure also received relatively high research effort for a wider variety of countries than Biological Resource Use, which predominantly received high relative research effort for countries in Sub-Saharan Africa. This suggests that the processes driving research effort towards these two threats are different.

In terms of Linear Infrastructure, observability and availability of potential interventions could have contributed to relatively high numbers of studies, whilst uncertainty over the severity of linear infrastructure for species-level extinction risk may limit the STAR score. There are a large number of potential threat abatement actions available (in-particular for roads, Glista, DeVault and DeWoody, 2009; Rytwinski *et al.*, 2016) which probably increases the motivation of relevant actors to map this threat, despite evidence supporting the effectiveness of such interventions being sparse (Rytwinski *et al.*, 2016; Dean *et al.*, 2019; Jones, Borkin and Smith, 2019). Legal obligations of major infrastructure projects to assess the threat of roads may also contribute, although the extent to which such planning-related assessments would be published in the scientific literature is uncertain. Linear Infrastructure impacts biodiversity through a variety of mechanisms, including direct mortality (Silva, Crane and Savini, 2020; Grilo *et al.*, 2021), fragmentation effects (Liu *et al.*, 2019; Pinto, Clevenger and Grilo, 2020), pollution (Schuler and Relyea, 2018; Krief *et al.*, 2020), and increasing susceptibility to other threats (e.g. roads facilitating agricultural and residential expansion, (Espinosa, Celis and Branch, 2018; Haider *et al.*, 2018; Sloan *et al.*, 2019). However, the longer-term impact on populations and species extinction risk remains uncertain (Holderegger and Di Giulio, 2010; Dean *et al.*, 2019). Further, some authors argue that studies failing to record negative effects of existing roads may indicate mass mortality that occurred between road construction and monitoring rather than low impact of the road (Ascensão *et al.*, 2019). Yet the reporting of transportation infrastructure as a major threat among species IUCN red list assessments is low compared with other threats (Maxwell *et al.*, 2016) and the indirect impacts of linear infrastructure via incursion of other human pressures may be absorbed into the STAR metric for other threats (Dean *et al.*, 2019). Therefore, we recommend that researchers planning to map the threat of Linear Infrastructure, if their aim is species conservation, consider whether investigating a different threat might yield more useful findings.

The bias towards studying Biological Resource Use in sub-Saharan Africa may be explained by several factors. Firstly, threat mapping studies in Africa were more frequently conducted at a multi-national scale than in other continents (see also Ridley *et al.*, 2022), increasing the occurrence of many African countries among those of high relative research effort, despite lower numbers of studies overall. Also, this finding could be conflating some sub-order taxonomic bias, in favour of medium to large-bodied species, as these are more likely to be subject to hunting or persecution (Rija *et al.*, 2020). Furthermore, the potential that this finding reflects a stereotyped view of the African conservation context should be considered. The assumption that natural resource use by indigenous communities is unsustainable and conflicts with conservation (e.g. bushmeat hunting, poaching, persecution, and retaliatory killing) is juxtaposed with the exploitative origins of most protected areas as colonial hunting reserves and continued international controversy over non-subsistence hunting (Garland, 2008; Domínguez and Luoma, 2020; Muller, 2021). The result is the pervasive, yet potentially erroneous, view that hunting is a dominant threat in this region. Our findings show that more research attention for other threats has a greater potential to reduce species extinctions among African countries, that have a relative lack of threat mapping studies overall. Further efforts to study the threat of Biological Resource

Use here, without investigating the potential benefit of addressing other threats, risks deepening harmful assumptions about the conservation context across continental Africa.

4.5.2. Mismatches where conservation need exceeded research effort

I found that country-threat combinations receiving the lowest relative research effort was Agriculture and Biological Resource Use in the tropical regions of the Americas, Asia, and Madagascar. Of these, relative numbers of threat mapping studies on Agriculture in Colombia, Ecuador, and Brazil remained low after the effects of land area and species richness were accounted for. The urgency to address the harmful effects of agriculture on biodiversity is echoed by many other studies (Perrings and Halkos, 2015; Maxwell *et al.*, 2016; Zabel *et al.*, 2019; Frick, Kingston and Flanders, 2020; Harfoot *et al.*, 2021), intergovernmental platforms (Brondizio *et al.*, 2019), and policy frameworks (CBD, 2021). In particular, agriculture in Colombia, which had the largest overall STAR score, has witnessed dramatic expansions in oil palm cultivation and post-conflict agricultural expansion over the last decade (Vargas *et al.*, 2015; Murillo-Sandoval *et al.*, 2021; Vanegas-Cubillos *et al.*, 2022), with some observed (Borón *et al.*, 2016; Pardo *et al.*, 2018) and many unknown (Vargas *et al.*, 2015) effects on biodiversity. Therefore, in the case of Agriculture in Colombia, the mismatch observed could be due to a combination of exceptionally high conservation need, recent conflict acting as a deterrent to researchers, and the rate of threat expansion being faster than the rate of scientific publishing. It should be noted that only threat maps published in English were included, likely contributing to the lack of studies found for some countries. Other probable reasons for countries being relatively understudied include limited access to human and technical resources- such as geographic information systems and sensing (Hilbert, 2016; Cavender-Bares *et al.*, 2022)- conflicting socio-political priorities affecting funding streams for research (Grau *et al.*, 2015; Giraldo, 2019; Vanegas-Cubillos *et al.*, 2022), and diverse landscapes of multiple, temporally and spatially interwoven human land-uses (e.g. logging, agriculture, road building, and residential development), making it difficult to distinguish (other) specific threats to biodiversity from overall land-use changes away from forest or other natural habitats (Brook, Sodhi and Bradshaw, 2008; Baldwin, 2010).

Although there was a mismatch between research effort and threat abatement potential in some geographic regions, Agriculture and Aquaculture was overall the most studied threat globally (see chapter 3). It should be noted that the literature search for the studies analysed here was completed in September 2020 and, for this chapter, was restricted to studies that were multi-national or smaller in scale. Therefore, threat maps published after 2020 (e.g. Guerrero-Pineda *et al*., 2022 and Slattery and Fenner 2021) and those that are global in scope (e.g. Harfoot et al., 2021 and Davison et al., 2021) may provide information on the threat of Agriculture and Aquaculture or for any other country-threat combination where relative research effort was lacking.

4.5.3. Drivers of research effort and implications for conservation

Our results showed that more threat mapping research effort has been directed towards country-threat combinations with larger STAR scores, land area, and species richness, with no significant effect of the extent of intense human pressure or socioeconomic variables. This suggests a preference for mapping threats in species-rich countries rather than countries with extensive human-modification. Given that 75% of land area is subject to intense human pressure (Venter *et al.*, 2016a), considerable expansion in human pressure is predicted (Meijer *et al.*, 2018; Chen *et al.*, 2020; Williams *et al.*, 2020), and some of the most biodiverse countries are also those with the most rapidly growing populations, reducing and mitigating threats in human-modified landscapes is critical. Similar tendencies for higher research output where there are lower levels of disturbance were found by Trimble and van Aarde (2012) and reiterated the concern that this could be hampering efforts to prevent species extinctions globally. Threat mapping can be as powerful a tool for monitoring threats in a proactive strategy, as it is for planning threat abatement actions reactively. Nevertheless, human disturbance is already too widespread to rely on pristine and protected areas alone to conserve global biodiversity. It is also possible that human pressure could be a more important driver of sub-national research effort than national scale effort, as human population and roads have been associated with recording effort on a sub-national scale by others (Mair and Ruete, 2016). Regardless, more effort is needed to map threats to species in areas subject to intense human pressure with the aim of planning threat reduction and mitigation actions.

Our work provides a data-driven method that facilitates the objective comparison of countries and threats for guiding decisions regarding future conservation research investment. This supports the implementation of the recently adopted Kunming-Montreal Global Biodiversity Framework by increasing the accessibility of data to decision-makers and informing actions to reduce threats to biodiversity (CBD, 2022a). The Parties to the Convention also agreed to strive towards the mobilization and efficient use of resources (CBD, 2022b), which is critical if the targets are to be achieved by 2030. As a contribution to the suite of considerations required to design robust research (Margoluis *et al.*, 2009), our approach provides a valuable empirical justification for allocating research resources within a country (among threats), and internationally (among country-threat combinations). This extends beyond filling knowledge gaps and includes synthesis of the collective findings where sufficient research is available (Grainger *et al.*, 2020). For example, Biological Resource Use in Indonesia represents a potential candidate for further evidence synthesis, due to its extremely high threat abatement potential and above average numbers of studies. As such, this approach supports the efficient use of resources by highlighting key areas for novel research as well as effective utilisation of existing data.

4.6. Conclusion

I present a quantitative approach to prioritising future threat mapping research, identify the main drivers of research effort, and highlight key areas of mismatch between research effort and conservation need. In a time of global climate and ecological crises, effective allocation of research resources is critical to inform transformative action, achieve global targets for 2030, and begin a positive trajectory towards 2050 and long-term biosphere resilience. All individuals or organisations involved in the production of research have the potential to prioritise progress towards biodiversity targets of the country in which they practice and the globally. If utilised this objective approach can help avoid the preconceptions, stereotypes, and biases that influence decisions surrounding study selection leading to more evidence-based and effective threat reduction activities.

Chapter 5: The intended conservation outcomes, recommended actions and stakeholder involvement in threat mapping studies

5.1. Abstract

There is often a mismatch between scientific outputs and the needs of decision-makers, hindering the ability of research to inform conservation action. Clearly defining the intended pathway from research to action and engaging stakeholders in the design and delivery of research have both been suggested as essential to ensuring that research is relevant to the needs of decision-makers. However, how often such practices are implemented is unclear. To address this knowledge gap, this analysis developed a semi-automated text-mining approach for retrieving and classifying sentences, and used it to enhance understanding of the pathways to action and stakeholder involvement reported in threat mapping studies. Sufficient analysable text was successfully extracted from the PDFs of 94% of relevant journal articles and the final vector-space model had a precision of 71% in retrieving relevant statements of intended outcome or recommended action. Studies intended to inform general conservation planning processes, tools and techniques more often than recommending specific conservation actions. For 68% of studies, general conservation planning processes, tools and techniques were the primary theme of intended conservation outcomes. Reports of stakeholder involvement were infrequent (present in 9% of studies) but those retrieved covered the design, planning, delivery, and validation stages of the research process. These findings present a valuable baseline for monitoring the use of clearly-defined pathways to action and stakeholder involvement in the threat mapping literature. I further highlight the underutilised potential of threat maps for identifying and refining specific candidate interventions as well as informing planning processes generally.

5.2. Introduction

Conservation science is an inherently applied discipline, in which the ability of research to inform policies and action is integral to its purpose (Soulé and Wilcox, 1980; Gibbons, Wilson and Green, 2011). Despite the rapidly increasing volume of knowledge generated through research (Plume and Van Weijen, 2014), there is often a significant delay or failure in translating these findings into effective policies or practical actions (Hering, 2018; Lavery *et al.*, 2021). Absent or inappropriate use of evidence in decision-making can, at best, risk sub-optimal allocation of financial, physical, and human resources, or, at worst, result in counterproductive decisions that harm the conservation objective (Pullin and Knight, 2003; Rose *et al.*, 2019). Closing the research-implementation gap in species conservation is key to maximising the efficacy of evidence-based conservation actions.

5.2.1. Barriers between research and implementation in conservation science

Multiple barriers contribute to the research-implementation gap across all stages of research production and use, from research design and delivery, through communication or knowledge mediation, to uptake into implementation (Nguyen, Young and Cooke, 2017; Walsh *et al.*, 2019; Nguyen, Ferreira and Klütsch, 2021). Barriers include: incompatible timing or scale (Jacobs, Garfin and Lenart, 2005), irrelevance to planning or policy priorities (Weichselgartner and Kasperson, 2010), lack of trust in researchers or research institutions (Cash *et al.*, 2003), and a lack of motivation, from either party, to engage in knowledge transfer (Cvitanovic *et al.*, 2015; Cvitanovic, McDonald and Hobday, 2016; Ferreira and Klütsch, 2021). Similarly, actions to overcome these barriers can be taken by actors across the knowledge-cycle (e.g. by individual scientists, boundary organisations, and decision-makers). At the scale of individual research studies, findings are more likely to be used by decision-makers if the study is relevant in time, space, and context, to the needs of decision-makers (Cash *et al.*, 2003).

One solution to enhance the relevance of research to decision-makers is designing studies with a clearly defined and communicated pathway to action. An example of an increasingly popular framework for doing this is 'Theory of Change' (Fullbright-Anderson, Kubisch and Connell, 1998; Mackenzie and Blamey, 2005). 'Theory of change' as a concept refers to the clear definition of measurable long-term goals and the outcomes and outputs required to meet those goals (Penfield *et al.*, 2014; Lavery *et al.*, 2021). For example, datasets and scientific publications (conservation science outputs) may lead to adoption of knowledge, skills or techniques (immediate outcomes), further leading to changes in management practices or policies (ultimate outcomes), with the overall impact of improving specific indicators of the state of biodiversity (impacts, Lavery *et al.*, 2021). Strict applications of a Theory of Change process include outlining all relevant actors and their responsibilities in achieving the goal, exploring how and why all possible outcomes may come about and articulation of assumptions (Allen, Cruz and Warburton, 2017; Phang, Failler and Bridgewater, 2020). Such extensive horizon scanning is often outside the scope of individual research studies, which may be why there has been limited uptake of the framework in conservation science (Rice, Sowman and Bavinck, 2020). Nevertheless, clear definition of the pathway to intended conservation outcomes makes the outputs of research more likely to be relevant to, and more easily interpreted by, decision-makers (Cvitanovic, McDonald and Hobday, 2016; Maron *et al.*, 2021; Wyborn and Evans, 2021).

Another way to enhance the relevance of research to the needs of decision-makers is engaging stakeholders in the conception, design, and delivery of research. Here, stakeholders are considered to be any individual, group, or organisation that either has the power to influence or is impacted by conservation policy or practice decisions. The bi-directional flow of knowledge through the knowledge-action cycle (also termed 'knowledge exchange', Mitton *et al.*, 2007) is regarded as critical to understanding how research informs action (Cvitanovic, McDonald and Hobday, 2016; Nguyen, Young and Cooke, 2017). Such engagement has also been found to increase cooperation and motivation for behaviour change, enhancing the long-term success of conservation projects (Hyman *et al.*, 2022; LeFlore *et al.*, 2022).

The manner of stakeholder engagement also impacts the likelihood of achieving conservation outcomes. A systematic review of studies investigating the impact of stakeholder engagement on conservation outcomes revealed complex dynamics that can help or hinder conservation objectives (Sterling *et al.*, 2017). Poorly conducted stakeholder engagements were found to: yield vague un-focused discussions (Büscher and de Beer, 2011), increase indecision due to participants' increased awareness of complexities (Gray *et al.*, 2012), misrepresent demographic variation (Gore and Kahler, 2012), increase frustration and distrust (Curtis *et al.*, 2014; Gaymer *et al.*, 2014; Minter *et al.*, 2014) and initiate or exacerbate social conflicts (Mbaiwa and Stronza, 2011; Mulrennan, Mark and Scott, 2012; Suich, 2013). Positive effects on behavioural change were observed where engagement from stakeholders was sought early and continued throughout the project, engagement was transparent, and stakeholder's knowledge and values influence decision-making (Sterling *et al.*, 2017).

5.2.2. Using existing research to monitor the use of science-implementation solutions

A key missing step in understanding whether current conservation research outputs are relevant to the needs of decision-makers is to understand the intended conservation outcomes (including specific action recommendations) of existing research. Several studies have reviewed the topics covered in the conservation literature systematically, including the composition of studies that are state, threat, or solution-focused (Fazey, Fischer and Lindenmayer, 2005; Godet and Devictor, 2018; Williams, Balmford and Wilcove, 2020). These agree that research on the state of and threats to biodiversity outweighs research on solutions (Fazey, Fischer and Lindenmayer, 2005; Williams, Balmford and Wilcove, 2020). Efforts are being made to rectify this. Sutherland *et al.* (2018) and (2020b) present syntheses of studies testing the effectiveness of different conservation actions. However, Williams, Balmford and Wilcove (2020) highlights that action can be taken at any stage in the development of knowledge from an understanding of the problem (threats, source, and drivers) to an understanding of responses (availability, implementation, and effectiveness). Further, in crisis disciplines, actions must often be taken on the best available, rather than complete, evidence (Stirling and Burgman, 2021). Yet, how existing conservation research that is not explicitly solution-focused intends to inform action in policy and practice is unknown.

A deeper understanding of the intended conservation outcomes of existing conservation literature could also be used to monitor the prevalence of known science-implementation barriers. For example, such information could be used to investigate the prevalence of poorly defined pathways to impact, mismatches in timing or scale, and relevance to stakeholders. Such monitoring would also help in overcoming science-implementation barriers (Rose *et al.*, 2018) and set a baseline against which progress can be assessed.

5.2.3. The science-implementation gap in threat mapping research

In few fields is it more important to understand this than in threat mapping. Reducing threats is a focal part of the Kunming-Montreal Global Biodiversity Framework, which features targets both on reducing threats and on ensuring the best-available evidence is accessible to decision-makers (CBD, 2022c). Yet, threat mapping has come under particular scrutiny for its ability to inform effective conservation actions. For example, Wyborn and Evans (2021) suggested that there was an overproduction of global maps that are too coarse in scale to inform on-the-ground conservation and in which the policy impacts are often overstated. Tulloch *et al.* (2015); Tulloch *et al.* (2020) also emphasised that the distribution of threats alone cannot inform a cost-effective conservation plan. The term 'threat mapping' has previously been used very broadly. Here, threat mapping studies are specifically considered to be studies that geographically present where threatening human activities impact wild animal or plant species (Ridley *et al.*, 2022). This definition gives threat maps intuitive potential to prioritise threats for abatement (reduction and mitigation) actions among locations. Threat maps also range widely in scope in terms of the species, locations, and threats involved, in a way that is representative of many patterns in conservation science generally (Ridley *et al.*, 2022). A deeper understanding of the intended conservation outcomes presented in individual threat mapping studies could yield powerful insights into the science-implementation gap in the production of threat maps and conservation science more broadly.

This work aimed to understand the intended conservation outcomes of threat mapping studies and the current effort applied to make the outputs relevant to the needs of decision-makers. I addressed this aim by firstly developing a semi-automated method for retrieving and classifying relevant statements from the threat mapping literature, then using the method to answer the following questions: (i) what intended outcomes are reported among threat mapping studies, (ii) to what extent is stakeholder involvement reported, (iii) what is the nature of reported stakeholder involvement, and (iv) is there an association between the intended outcomes and the threat studied or whether stakeholders were involved?

To answer these questions I developed and applied a semi-automated text mining approach. Text mining offers a promising suite of techniques for retrieving and classifying text data from large volumes of scientific literature. Such tools, have been used to retrieve and classify outcomes and recommendations in other fields such as health (Tellería, Ilarri and Sánchez, 2020; van Laar *et al.*, 2020; Ahadh, Binish and Srinivasan, 2021) and marketing (Guerreiro and Rita, 2020). Although, text mining approaches have been applied to other tasks in ecology and conservation (Farrell *et al.*, 2022), the retrieval and analysis of intended outcomes and stakeholder involvement has not yet been attempted.

5.3. Methods

5.3.1. Overview of methods

A three-step process implementing multiple text-mining and natural language processing techniques was used to identify, extract and classify statements of intended outcome (including specific recommendations) and stakeholder involvement in the threat mapping literature. Step one involved extracting unstructured text data from the source documents such that it was in the correct reading order and refining to text from the main body of the article. In step two, statements of intended outcomes or stakeholder involvement were retrieved from all main-body text. In step three, the words present in relevant statements were used to thematically classify them, utilising the IUCN framework of recommended actions (IUCN, 2006; Salafsky *et al.*, 2008) to classify specific actions among intended outcomes.

5.3.2. Pre-processing text data

5.3.2.1. Extraction

The source of text analysed here was Portable Document Format (PDF) files of the 1,011 journal articles found through the systematic mapping of literature that maps threats to species by Ridley *et al.* (2022). Ridley *et al.* (2022) systematically searched multiple peer-reviewed and grey literature sources for threat maps published 2000 – 2020, and classified their attributes across 22 different variables, capturing the geography, taxonomy, and threats studied. All text present in the PDFs was rendered to characters using the PDF rendering engine Poppler (2023). Text from three PDFs could not be extracted in this way. For these, PDFs were converted into an image and text was extracted using the open source text recognition (OCR) engine, Tesseract (2021). Both types of text processing engine were accessed via the package pdftools (version 3.3.3,Ooms, 2023) in R (version 4.2.1). PDFs were manually classified into eight format types (Fig 5.1) and a bespoke method of reassembling the text in the correct reading order across sections, columns, and pages was developed for each format type. Two format types were excluded from further analysis due to low prevalence (‘*2b’*, 3 studies, and ‘*3’*, 4 studies) as well as six PDFs that were incorrectly labelled as journal articles in the bibliometric data extracted from Ridley *et al.* (2022).

5.3.2.2. Cleaning

Section headings were identified through regular expression pattern matching of whitespace and a comprehensive set of common section names (Abstract, Introduction, Methods etc.). Once in the correct reading order, extracted text was transliterated to ASCII characters and cleaned to remove: publication-specific information, download notices, dates, author names, correspondence information, institutional addresses, websites, numerical codes (e.g. doi and ISSN numbers), and the contents of parentheses. Non-initialised names (e.g. ‘First-name Surname’) could not be removed as there was no pattern that could distinguish these from other relevant text. All text occurring before the abstract and after the references heading was removed. Individual articles were split into sentences, were converted to lowercase, and all excess punctuation was removed apart from hyphens and full-stops.

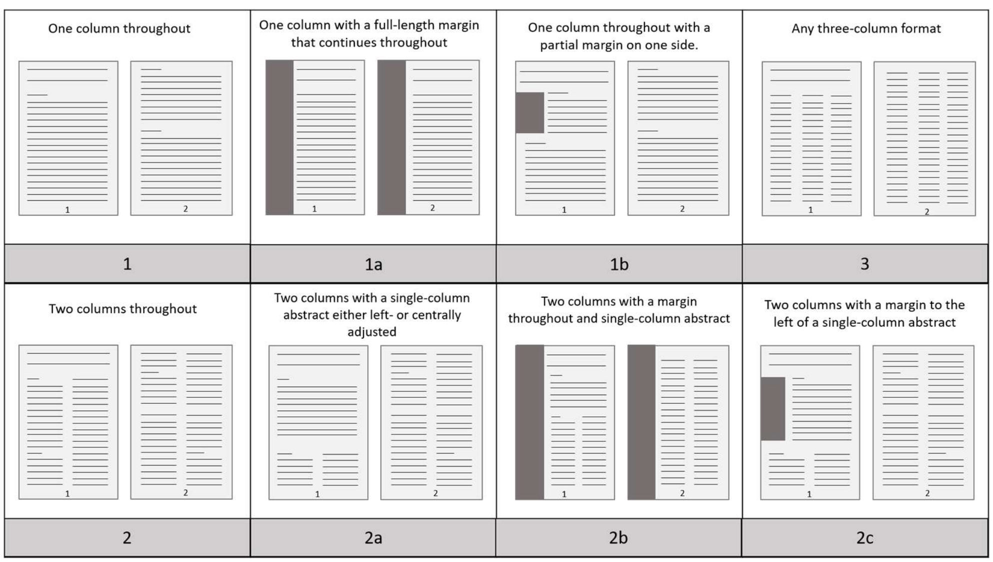

Figure 5.1. Schematic representation of PDF format types identified as relevant to coherent text extraction. Dark grey shaded sections indicate margins of non-target text.

Additional text cleaning was performed at the sentence-level. Sentences were removed if they had fewer than five words or a length in characters greater than the upper bound as described below (section 4.2.3). The words in each sentence were lemmatised and tagged with grammatical attributes using the English Web Treebank (English-EWT, Bies *et al.*, 2012).

Lemmatisation is a process of reducing words down to their root form (lemma). In contrast to 'stemming' which removes characters after the root form of the word, lemmatisation considers the context and can replace characters as necessary. For example, *studies* stemmed is *studi* but lemmatised is *study*. The use of either of these processes is standard practice to reduce variation among terms in the vocabulary that convey the same or very similar meaning (Boban, Doko and Gotovac, 2020; Banks *et al.*, 2022).

English-EWT is trained on a library of over 16,000 sentences and over 250,000 words making it the largest English treebank under the Universal Dependencies framework (universaldependencies.org, 2014). Sentences were removed if they didn't contain any main or auxiliary verbs.

5.3.2.3. Outlier detection

The quality of text extraction and cleaning was validated using a combination of iterative manual screening and detection of outliers in total length of extracted text, numbers of sentences per article, length of extracted sentences and proportion of outlier sentences per article. Tukey's fence method was used to detect outliers, where 1.5 times the interquartile range above the third quantile and below the first quantile indicated the upper and lower bounds respectively (Tukey, 1977). Both bounds did not always indicate extraction errors depending on the metric being assessed. Sentences were considered outliers if the number of characters was outside either the upper or lower bound. Articles were excluded if: the overall number of characters was less than the lower bound, the number of sentences was less than the lower bound, or the proportion of sentences that were outliers was greater than the upper bound. The relationship between the total number of characters extracted for each article and the number of sentences per article was also visualised but did not reveal any additional outliers. Articles and sentences found to be outliers were manually checked before removal to verify that extraction or cleaning errors were the cause of outlying values. 130,568 sentences among 949 articles remained after outlier removal, representing 94% of the original sample (of 1,011 articles total).

5.3.3. Retrieval of relevant statements

Information retrieval describes a group of text-mining algorithms for finding (retrieving) relevant texts (usually documents) from a collection, based on the matching of each of those documents to a user-defined query (Ceri *et al.*, 2013). Information retrieval models form the basis of most modern search engines, classic examples of which are the Boolean Model and the Vector Space Model (Ceri *et al.*, 2013).

5.3.3.1. Intended outcomes and recommended actions

5.3.3.1.1. The vector space model (VSM)

A vector-space model (VSM) was used to retrieve sentences pertaining to a recommended action or intended outcome (actions for simplicity). A VSM was chosen due to its ability to use a large number of terms in the query and rank sections of text by similarity to that query (Zong, Xia and Zhang, 2021). A threshold of minimum similarity was then be applied, whereby sentences with a similarity higher than the threshold were retrieved and those with a similarity lower than the threshold were not retrieved. For a VSM both the sentences to be queried and the query are each represented by a vector of the same dimensions as the total shared vocabulary (number of unique terms). Sentence vectors were populated with the weighted frequencies of each term and each query vector was populated with the binary relevance of each term (0 or 1, where 1 is relevant). As such, a sentence containing multiple relevant terms, and high weighted frequencies of those terms, would have a higher similarity to the query than a sentence with low numbers and low weightings for relevant terms. Cosine similarity was used to evaluate the similarity between each sentence and the query. Cosine similarity is calculated as the cosine of the angle between two vectors, which equates to the dot product divided by the product of the magnitudes of the two vectors (Zong, Xia and Zhang, 2021).

The weighted term frequency (tf-isf) for each sentence was the term frequency (tf, term count divided by sentence length) multiplied by the inverse sentence frequency (isf, i.e the inverse of the proportion of sentences the term occurred in). As such, a term that occurred in a large proportion of sentences received a lower tf-isf than a term that occurred in a low proportion of sentences where the term frequency was the same. This prevented the retrieval model being biased towards terms that were common overall. The use of this weighted term-frequency metric is standard practice in document retrieval (Allan, Wade and Bolivar, 2003; Qaiser and Ali, 2018; Lavin, 2019) and has been successfully applied to the retrieval of sentences (Doko, Štula and Seric, 2015; Boban, Doko and Gotovac, 2020).

5.3.3.1.2. Additional text pre-processing and action labelling

The terms used to construct and evaluate the VSM were nouns, main verbs, auxiliary verbs, adjectives, or adverbs. Hyphenated words were converted to single words and all remaining punctuation was removed. English words that are known not to convey thematic information (stopwords, Karl, Wisnowski and Rushing, 2015) were removed with the exception of auxiliary verbs. The final input to the VSM was a sentence-term matrix populated with the tf-isf of each term per sentence. The total shared vocabulary consisted of 48,386 unique terms with each sentence containing on average 14 (mean ± sd = 13.5 ± 5.5) unique terms.

A training sample of 2,413 labelled sentences among 735 articles was used to develop the VSM. Sentences were labelled based on whether the sentence included an intended outcome or recommended conservation action from the considered study (herein, actions) or did not (non-actions). Sentences were labelled as 'non-actions' if the sentence explicitly referred to a different study or body of work, or if the sentence recommended further academic research without an explicit pathway to implementation in conservation. 988 sentences (among 456 articles) in the training set were actions and 1445 sentences (among 648 articles) were non-actions.

5.3.3.1.3. Developing and selecting the query

The training sample was used to generate five candidate queries (Appendix D.1). Two were generated manually; both were constructed from terms present in sentences labelled as actions, and one included synonyms of those terms. A further two queries were generated using an algorithm that added terms to the query if the mean tf-isf was higher in action sentences than in non-action sentences accounting for standard deviation. For the second of the algorithm-derived queries, the mean tf-isf in actions had to be at least double the mean tf-isf in non-actions for terms to be included in the query. A final query exclusively contained modal verbs (e.g. would, should, could) to test the isolated potential of modal verbs for identifying action statements.

The five candidate queries were compared by testing the difference in cosine similarity between sentences labelled actions and sentences labelled non-actions, and measuring the recall, precision, and F1-score across 20 different thresholds of cosine similarity ranging from 0.0001 to 0.1. The threshold represented the minimum cosine similarity required to retrieve an action sentence. Recall was the proportion of all true action sentences that were retrieved by the model and precision was the proportion of sentences retrieved by the model that were true action sentences. The F1-score was used as a combined metric of model performance, calculated as the harmonic mean of precision and recall (Zong, Xia and Zhang, 2021).

The final query and similarity threshold were chosen based on the ability of the query to discriminate between actions and non-actions and the precision achievable without compromising recall. The final model was tested by applying the query to all remaining unlabelled sentences and the 1000 sentences with the highest cosine similarity were manually screened. Final performance was evaluated as the proportion of the testing sentences that were true action sentences.

5.3.3.2. Boolean retrieval of stakeholder involvement

Statements of stakeholder involvement were identified using a Boolean information retrieval model in which sentences were retrieved if either the terms ‘stakeholder’ or ‘expert’ were present. This approach was expected to be more efficient at finding relevant sentences than a VSM due to the lower expected frequency of statements on stakeholder involvement across the document collection and the lower number of relevant query terms. In an attempt to capture sentences referring to human communities, the inclusion of ‘communit’ in the search terms was trialled, but excluded, as it returned a further 3,000 sentences that were mostly referring to animal or plant communities or were not otherwise relevant. The final 1,439 sentences retrieved were manually screened.

To be considered a statement of stakeholder involvement, sentences had to indicate that stakeholders (e.g. conservation practitioners, experts, governing bodies, and people living and working in affected areas or industries) were involved in the design, development, or delivery of the study. This specifically did not include sentences that indicated a) stakeholders, experts, or communities were the source of the data that was analysed (e.g. threats mapped based on surveys of the local community), or where direct involvement of stakeholders in the research process was not stated but b) their needs were considered or c) the method, approach, or findings were intended for use by stakeholder groups. The prevalence of each of these specific types of irrelevant statements was recorded. Sentences were excluded entirely if the sentence explicitly referred to a different study or body of work, was incoherent, or did not convey useful information about stakeholder involvement in the study for any other reason. A common other reason for exclusion was that the sentence expressed the importance of stakeholder involvement generally without indicating if stakeholders were involved in that particular study.

5.3.4. Text classification

5.3.4.1. The Latent Dirichlet Allocation (LDA) topic model

A Latent Dirichlet Allocation (LDA) topic model was used to predict the thematic structures within the action-specific text among the studies. Topic Modelling is a powerful and widely-used method for quickly uncovering what topics are present in large sets of text data, for which Latent Dirichlet Allocation (LDA, Blei, Ng and Jordan, 2003) is one of the most commonly used algorithms (Jelodar *et al.*, 2019). LDA topic modelling lends itself well to classify outcomes among articles as the model allows each term to occur in multiple topics and each article to contain multiple topics. LDA models traditionally generate a specified number of topics without any prior information from the user on the topical structures expected (unsupervised). 'Seeded' LDA topic models extend the traditional LDA model and allow the incorporation of prior information on topical structures through user-specified 'seed words' (Jagarlamudi, Daumé III and Udupa, 2012).

5.3.4.2. Semi-seeded classification of intended outcomes or recommended actions

The sentences retrieved using the VSM were combined with the training dataset, resulting in a sample of 1,667 labelled actions among 550 articles to use in action classification. Sentences were split into individual words and cleaned in the same way as for information retrieval, with the exception that only main verbs and nouns were included, resulting in a vocabulary of 1,017 unique terms. An article-term matrix was populated with the frequency with which each term occurred in each article, considering only the text from action sentences.

A model with 20 seeded and 15 unsupervised topics was fitted to the action-specific text. A combined approach was used here in an attempt to capture specific recommended actions as well as broader concepts relevant to the framing and interpretation of intended outcomes. Seeded topics were based on the IUCN Red List Classification of Recommended Actions (Salafsky *et al.*, 2008) and five seed words per topic (Appendix D.4) were allocated manually based on the wording of the classification scheme and terms available in the action vocabulary. The IUCN Classification of Recommended Actions is a hierarchical framework and different levels in this hierarchy were used depending on the keywords available and the ability to distinguish them. Three additional topics not covered in the framework were seeded in an attempt to capture articles that sought to influence biodiversity conservation planning in general, intended their method or technique to be directly applied, and recommended monitoring. Monitoring is covered by the IUCN Classification of recommended research rather than action.

As the same number of seed words needed to be specified for each seeded topic, and there were large differences in numbers of potential keywords among actions in the IUCN framework, some terms were replaced with synonyms. For example, ‘bycatch’, ‘hunting’, and ‘fishing’ were all replaced with ‘harvest’. A conversion table for all term replacements is provided in Appendix D.2.

5.3.4.3. Unsupervised classification of stakeholder involvement

An entirely unsupervised LDA topic model was used to uncover themes in the 155 sentences among 89 studies that indicated stakeholder involvement in the design or delivery of the threat mapping studies. An unsupervised approach was appropriate here as there were no prior expectations about the distribution of topics. The same cleaning process was applied to statements of stakeholder involvement as was applied to actions (section 4.4.2 above) resulting in a vocabulary of 291 terms. Models predicting 10, 15, and 20 topics were compared based on their perplexity (a measure of reliability where low values are preferred, Newman *et al.*, 2009) and the interpretability of the five highest ranking terms per topic. The models predicting larger numbers of topics had lower perplexity but a smaller number of topics was found to be more interpretable. The 10-topic model was also considered more appropriate due to the small sample size.

5.3.4.4. Topic interpretation, prevalence, and specificity

The unsupervised topics for both actions and stakeholders were interpreted based on the five terms that had the highest likelihood of occurring in each topic (term-topic weight). Prevalence of each seeded or unsupervised topic across both models was measured as the number of articles each topic occurred in. Whether a topic occurred in a particular article was assessed based on the assigned weight of each topic within each article assigned by the model (article-topic weight). An action topic was considered to occur within an article if the topic was among the five highest ranking topics for that article. A stakeholder topic was considered to occur within an article if it was among the three highest ranking topics for that article. The choices of five and three topics were established by exploring the relationship between the article-topic weight and the rank in the article for each model.

Topic specificity and generality was assessed visually to aid interpretation of action topics. The mean article-topic weight among articles where each topic was the highest-weighted topic was plotted against the mean weight among articles where each topic was present but not the highest-weighted. Topics with high mean weight in articles where they were the top-ranked, but low in articles where they were not are likely to be specific topics. Topics with high mean weight when not the highest-weighted topic and low mean weight when they were the highest-weighted topic are likely to be general topics (Westgate *et al.*, 2015).

5.3.5. Association between threats, outcomes, and stakeholder involvement

The association between threats studied, outcomes, and stakeholder involvement was measured as the flow in studies between themes of each of these variables for those studies where at least one action statement was retrieved (n= 550). Themes for actions and stakeholder involvement were allocated when interpreting the text classification output. For threats, themes were taken to be the class at level 1 in the hierarchical classification (Salafsky *et al.*, 2008). Information on the threats studied was collected as part of the systematic mapping process and categorised according to the IUCN Red List Threat classification scheme (Salafsky *et al.*, 2008; Ridley *et al.*, 2022). Here, an action was considered to be present in the study if it was within the five highest weighted topics for that article and a stakeholder-topic was considered present if it was within the three highest weighted topics for that article. Flows of studies were visualised and the association between actions and each of threats or stakeholder involvement were tested using Chi-squared test of independence (McHugh, 2013).

5.4. Results

5.4.1. Retrieval of relevant statements

5.4.1.1. A vector-space model for retrieving action statements

All five candidate queries (Q1-Q5, Appendix D.1) had significantly different mean cosine similarity, though none could perfectly differentiate, between action sentences and non-action sentences (Table 5.1, Fig 5.2). Q1 and Q2 showed the greatest difference in mean cosine similarity (Table 5.1, Fig 5.2). Action-statements were less similar on average to Q2, which included synonyms, than to Q1 which did not include synonyms. Substantial proportions of action sentences bore no similarity to Q3 (i.e cosine similarity = 0, where action tf-isf > non-action tf-isf), Q4 (action tf-isf > 2*non-action tf-isf), or Q5 (modal verbs only, Fig 5.2).

In terms of maximum precision and recall achieved, the best performing query was Q1 with a maximum F1-score across all similarity thresholds of 0.753, closely followed by Q2 with 0.748 (Table 5.1). Both Q1 and Q2 had a maximum recall of 100% and high maximum precision with 82% and 91% respectively. For Q1, the precision at maximum recall was approximately 50%, and recall at maximum precision was approximately 45% (Fig 5.3). For Q2 the precision at maximum recall was also approximately 50% but recall at maximum precision was approximately 12.5% (Fig 5.3).

Query		Length (words)	Maximum achieved across similarity thresholds			Test for difference in cosine similarity		
			Precision	Recall	F1 Score	df	t-value	p
1	Manually identified keywords	344	0.827	1.000	0.753	2288	37.81	<0.001
2	Manually identified keywords + synonyms	569	0.917	1.000	0.748	2326	37.56	<0.001
3	Difference in mean tf-isf	193	1.000	0.430	0.560	1161	19.36	<0.001
4	Difference in mean tf-isf with multiplier	185	1.000	0.412	0.552	1142	19.21	<0.001
5	Modal verbs	8	0.630	0.579	0.584	1891	13.37	<0.001

Table 5.1. Comparison of candidate action-retrieval queries across 20 cosine similarity thresholds ranging from 0.0001 to 0.1. Difference in similarity was tested using an unpaired t-test between sentences labelled as actions and sentences labelled as non-actions.

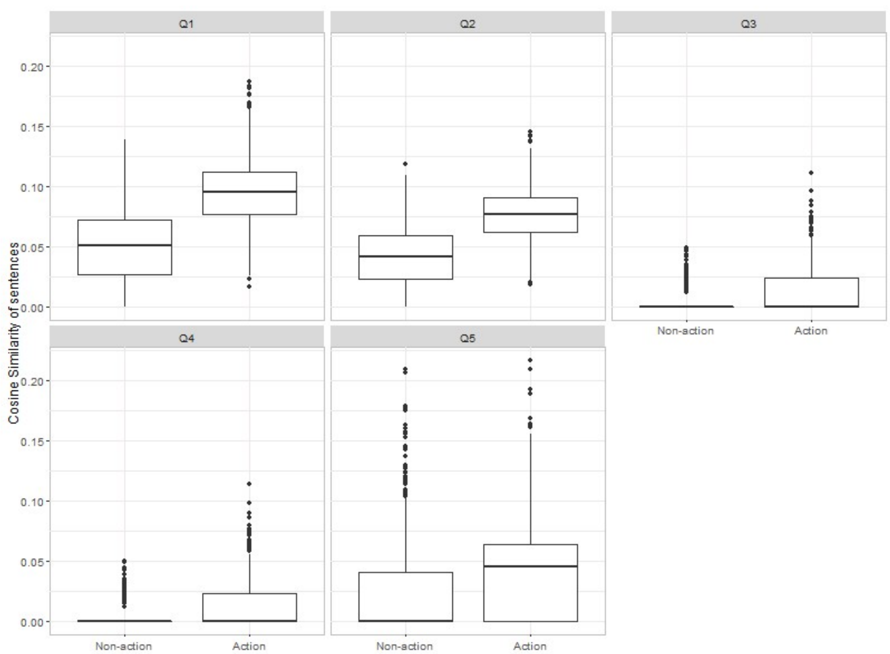

Figure 5.2. Cosine similarity between each of five queries (Q1-Q5) and sentences labelled as either actions or non-actions. Q1 = keywords manually selected from a sample of labelled actions Q2 = Q1 plus manually found synonyms, Q3 = algorithm-based with no multiplier, Q4 = algorithm-based with multiplier, Q5 = modal verbs only.

Of the five candidate queries, only Q1 and Q2 performed as expected in response to differing minimum thresholds of cosine similarity required to automatically retrieve potential action-sentences (hereafter simply 'threshold'). It is expected that at a low threshold, recall will be high and precision low. As the threshold increases, recall would be expected to fall and precision rise with the maximum overall performance (F1-score) being achieved approximately where recall and precision become equal. In the case of Q3 and Q4 at the lowest considered threshold (0.0001), precision was higher than recall and diverged further as the threshold increased (Fig 5.3).The query constructed from modal verbs only (Q5) did not behave as expected but showed stable performance at similarity thresholds between 0.0001 and approximately 0.03, where precision and recall were both approximately 60% (Fig 5.3). The precision of Q5 remained stable across all tested thresholds (Fig 5.3).

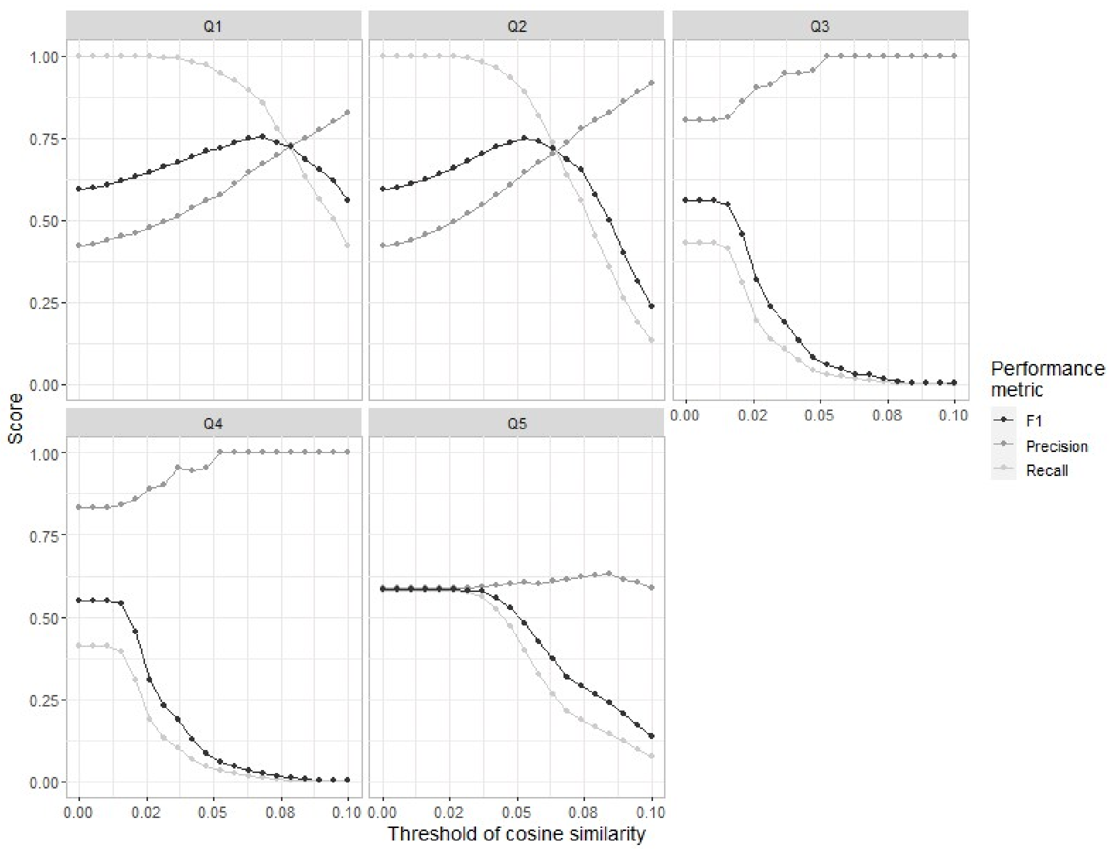

Figure 5.3. Recall, precision, and F1-score of five candidate queries (Q1-Q5) across different minimum similarity thresholds required for sentence retrieval. Similarity is the cosine similarity of the query to all each sentence. Recall is the proportion of all relevant sentences that were retrieved, precision is the proportion of retrieved sentences that were relevant, and F1-score is an overall performance metric combining both precision and recall.

As the goal of this analysis was to retrieve and classify a representative sample of action sentences the final query and threshold was chosen to prioritise precision without compromising recall. Therefore, the final VSM was implemented using Q1 and a cosine similarity threshold of 0.095. The final VSM had a precision of 80.2%, recall of 50.4%, and an F1-score of 0.62 on the training sentences. The final model retrieved 2,056 unlabelled sentences among 649 articles, 71% of which were relevant. Across the training sample and VSM-retrieved sentences, 1,667 relevant action sentences were retrieved among 550 articles, representing 60% of all included articles (Fig 5.4).

5.4.1.2. Stakeholder involvement in design or delivery

155 sentences among 89 studies were found to indicate that stakeholders were involved in the design, or delivery of the threat mapping study in question (Fig 5.4). This represented 10.8% of all the sentences containing the terms ‘stakeholder’ or ‘expert’, and 9% of all included articles. The greatest percentage of retrieved sentences indicated that stakeholders were the source of the data that was analysed (42.5%). A further 2.8% indicated that the needs of stakeholders were considered but not that stakeholder were directly involved, and 5.6% indicated that the study method or findings were intended for direct use by stakeholder groups.

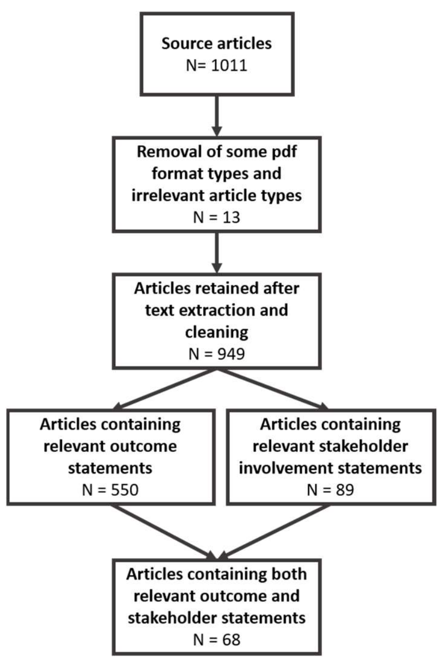

Figure 5.4. The flow of articles through text extraction, cleaning and information retrieval stages.

5.4.2. Classification of relevant sentences

5.4.2.1. Intended outcomes and recommended actions

All 16 topics seeded from the IUCN recommended actions and the four additional seeded topics were detected along with 15 unsupervised topics. The unsupervised topics covered a range of themes including Management of Threats, Data Tools and Techniques, Conservation Planning Processes, and Law, Policy, and People (Appendix D.4). Including the seeded topics, Protection and Management of Species, Sites, or Resources, were also captured (Appendix D.4).

Topics on the theme of Conservation Planning Processes and Data, Tools, and Techniques tended to be the most prevalent (Fig 5.5), occurring in 509 (93%) and 384 (70%) articles respectively. These two themes were also the highest ranked themes in 259 (47%) and 117 (21%) articles respectively. Topics on the theme of Law, Policy, and People were the least prevalent, occurring in 108 (20%) articles and top ranked in 10 articles (2%).

The action-topic that occurred in the largest number of articles was Biodiversity Conservation Planning, which occurred in 186 of the 550 articles (34%). The topics with the lowest prevalence were: Compliance and Enforcement (14 articles, 2.5%), Education and Awareness (19 articles, 3.5%), and Livelihood, Economic, and Other Incentives (19 articles, Fig 5.5). Specifically-defined interventions such as: Species Reintroductions (30 articles), Limiting (Problematic) Species Population Growth (31 articles), Capacity Building (33 articles), Harvest Management (40 articles) and Invasive Species Control (51 articles) occurred in fewer studies than more conceptually broad topics such as: Land or Water Protection (95 articles), Developing Strategies (122 articles) and Identifying Priorities (133 articles, Fig 5.5). With the exception of general biodiversity conservation, unsupervised topics occurred in more articles than seeded topics (Fig 5.5).

Most topics had a higher mean weight among articles where they were the highest ranked topic than the mean weight among articles where they were ranked in any other position; a difference that was most pronounced for unsupervised topics (Fig 5.6). This indicated that more topics were discussed specifically than were discussed generally, and unsupervised topics tended to be discussed more specifically than seeded topics. The only exceptions were two IUCN-seeded topics that weren't the highest ranked topic for any article (Topic 16: Compliance and Enforcement and Topic 17: Livelihood, Economic, and Other Incentives, Fig 5.6).

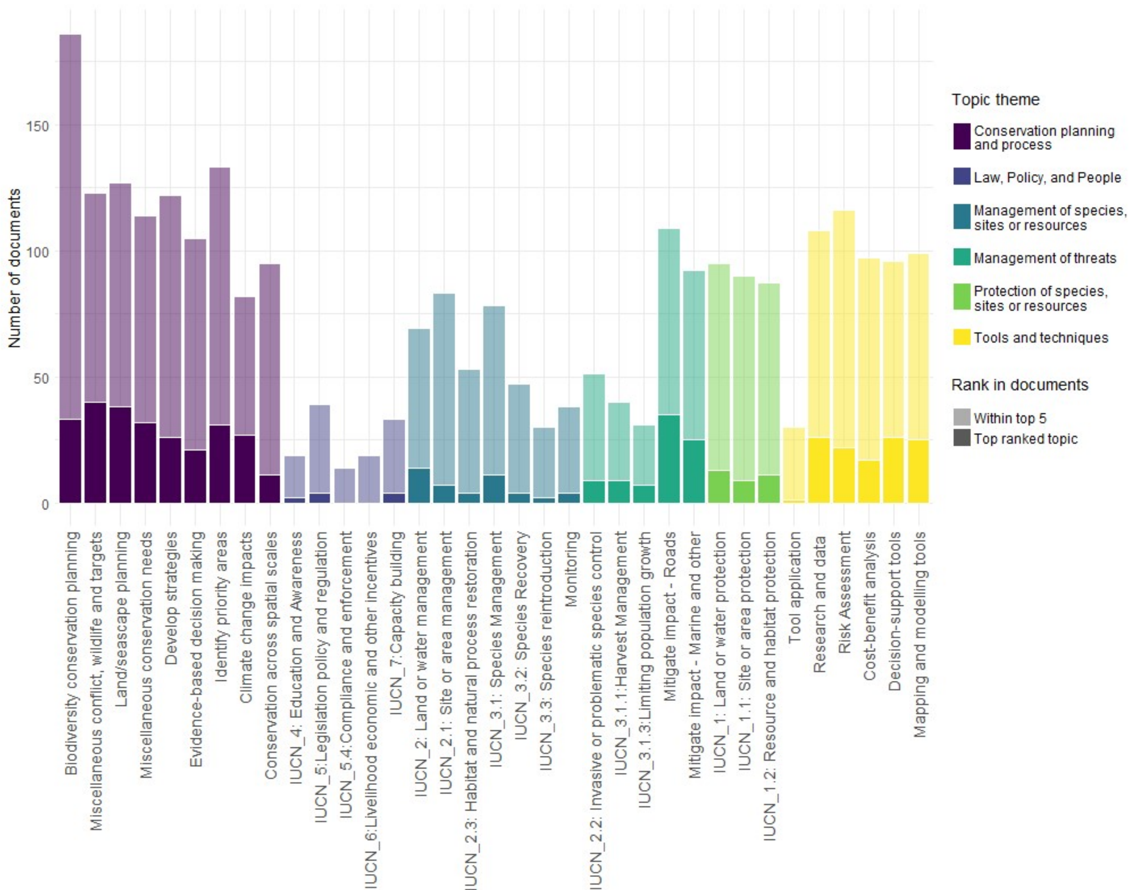

Figure 5.5. Prevalence of topics among statements of recommended actions and intended outcomes retrieved from the threat mapping literature. Prevalence is measured as the total number of articles for which the topic is within the five highest ranking topics. N = 550. Topics seeded from the IUCN framework of recommended actions are indicated.

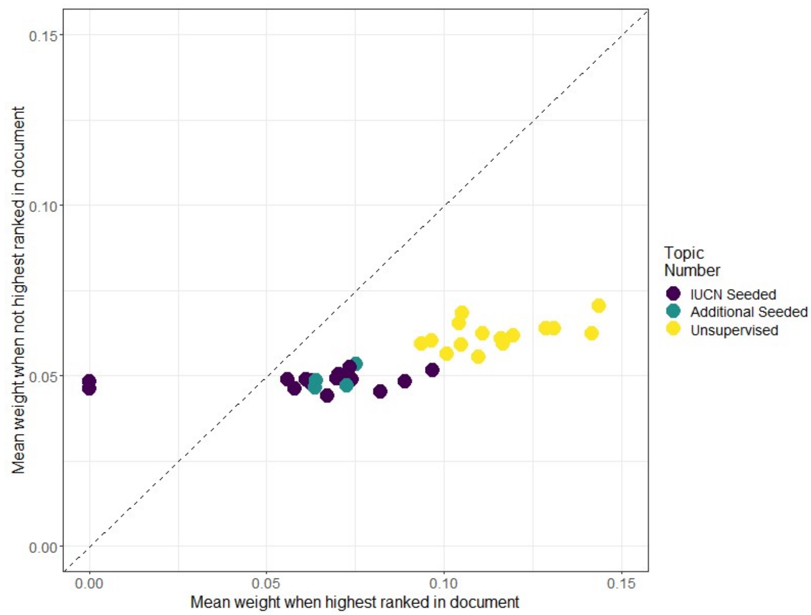

Figure 5.6. Topic specificity and generality. Topics 1-20 were seeded using the IUCN framework of recommended actions, topics 21 to 35 were allocated by unsupervised classification. Weight indicates the weight of each topic within each article.

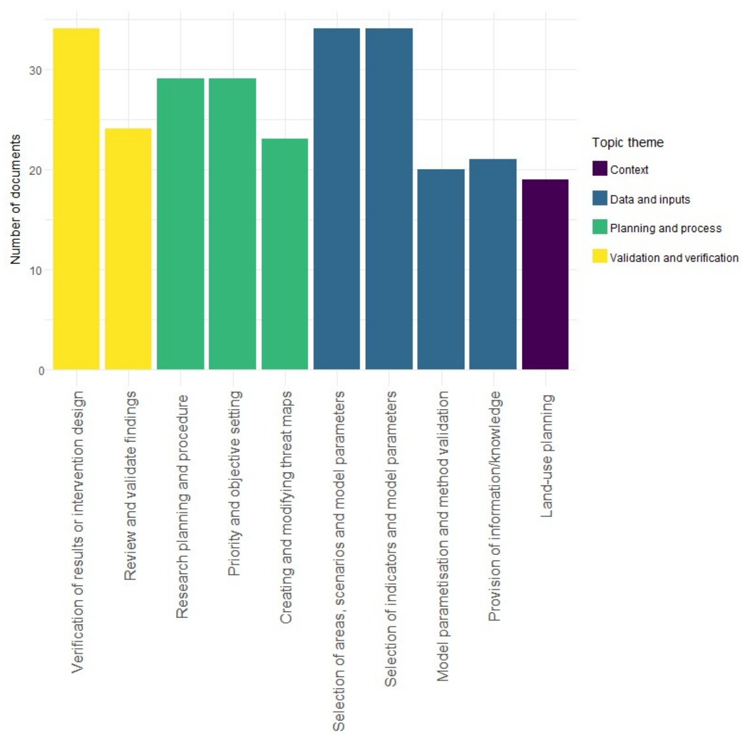

Figure 5.7. Prevalence of topics among statements of stakeholder involvement measured as the number of articles for which each topic was within the top three highest weighted topics. N = 86.

5.4.2.2. Statements of stakeholder involvement

Ten topics were generated from text contained in statements of stakeholder involvement in the design and delivery of threat mapping studies. These were broadly grouped into involvement with Data and Inputs, Planning and Process, and Validation and Verification (Appendix D.5). There was one topic that seemed to be derived from the context of the study rather than the manner of stakeholder involvement and so was assigned the theme 'Context'.

The number of articles that each topic occurred in was relatively balanced among topics. Stakeholder topics were considered to occur in an article if that topic was within the three highest weighted topics for that article. With the exception of one context-related topic, each topic occurred in between 20 and 40 articles (Fig 5.7). The least prevalent topic was Model Parametrisation and Method Validation and the most prevalent were: Verification of Results or Intervention Design, Selection of Areas, Scenarios and Thresholds, and Selection of Indicators and Parameters.

5.4.2.3. Association between the intended outcomes, stakeholder involvement and threats studied?

The flows in articles among actions and each of threats and stakeholder involvement were approximately proportional to the prevalence of each level of each variable (Fig 5.8). There was no significant association between action themes and types of stakeholder involvement, $X^2_{(15,\, n = 550)} = 5.42$, $p = 0.988$) and no significant association between threats and outcomes/actions, $X^2_{(45,\, n= 550)} = 37.44$, $p = 0.78$) identified.

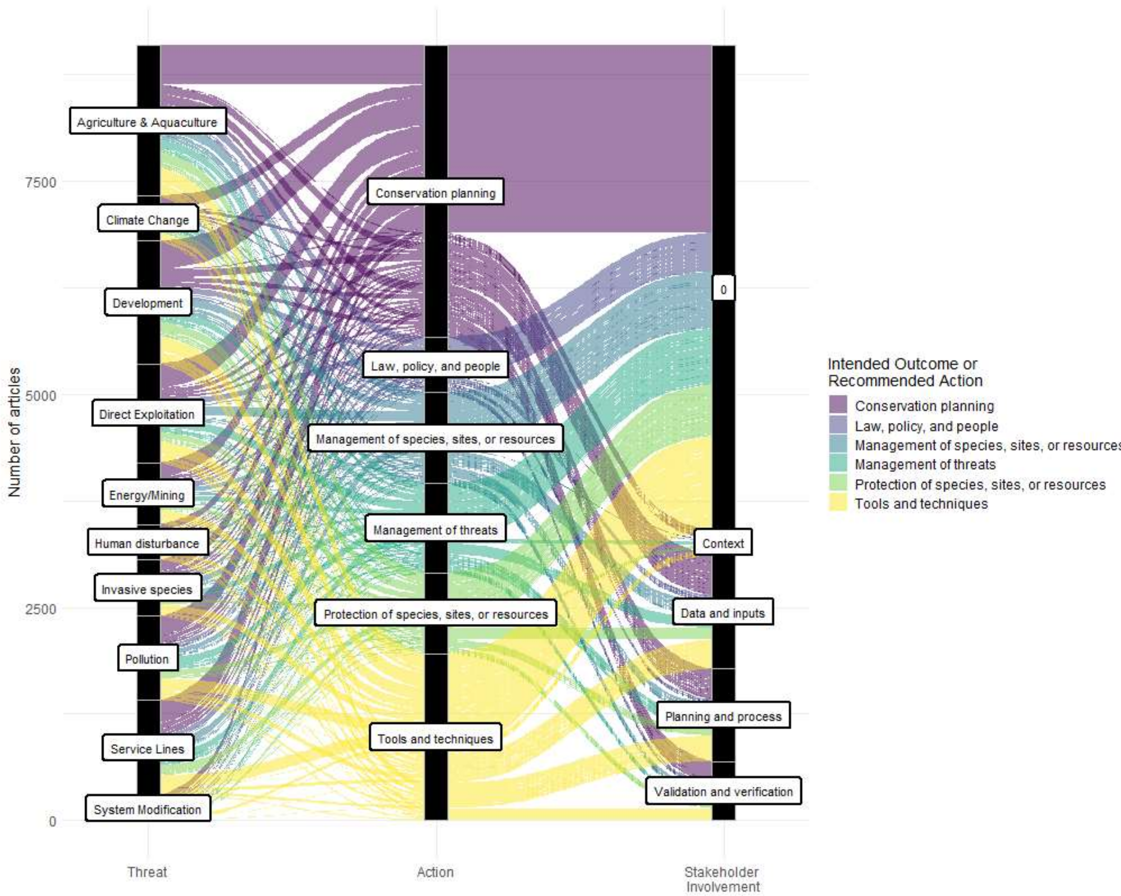

Figure 5.8. The flow of studies among actions, threats, and stakeholder involvement for action classes identified by the latent Dirichlet allocation (LDA) topic model. Each study recorded between one and 20 threats, up to 5 action topics, and up to three stakeholder topics. Stakeholder Involvement = '0' indicates that no statement of stakeholder involvement was retrieved.

5.5. Discussion

This investigation developed a novel approach for retrieving and classifying sentences, and use it to gain an understanding of the intended outcomes and stakeholder involvement reported in the threat mapping literature. Threat mapping studies intended to inform conservation planning processes, tools and techniques more often than they recommend specific actions. Reports of stakeholder involvement were infrequent, but those retrieved covered a range of stages across the process of research design and delivery. There was no association between the reported outcomes and stakeholder involvement or particular threats.

5.5.1. Prevalence of defined pathways to action

These findings show that pathways to action are present but often unclearly or partially defined in the threat mapping literature. Outcome statements were retrieved from 60% of included articles using a model that retrieved 50% of relevant sentences from the training data. Given that a model using the same query could achieve a maximum recall of 100% using a lower threshold of similarity, it is likely that retrievable outcomes were present in all included articles if recall was prioritised over precision in model specification. However, among the retrieved sentences, there was a strong focus towards conservation planning processes, tools, and further assessment.

Conceptually specific topics that gave the strongest direction for action in conservation planning and policy were the least prevalent (e.g. education and awareness, species reintroduction, and monitoring). This suggests the need for more clearly-defined pathways to action (Cvitanovic, McDonald and Hobday, 2016; Maron *et al.*, 2021; Wyborn and Evans, 2021). It could be argued that there are often multiple pathways to implementation from one piece of knowledge and it is not the job of scientists to prescribe what these should be However, without a defined pathway to action, it is difficult to assess whether intended outcomes are aligned with the needs of stakeholders and whether study design is conducive to achieving those outcomes. Furthermore, by engaging stakeholders in defining the intended pathway to action, the proposed intervention is more likely to be appropriate and feasible. Designing research without any implementation pathway in mind, risks producing research that does not directly inform any actions.

The prevalence of conservation planning processes, tools, and techniques within outcome statements also suggests that authors perceive the value of threat mapping to be informing intermediary planning processes, and research rather than direct action. This echoes findings from climate science communication about the close interaction between uncertainties, need for more information, and inaction (Constantino and Weber, 2021). Across crisis disciplines decision-delay can cause as much harm as decisions made under a lack of information (Waring *et al.*, 2020). Conservation may have limited resources that need to be prioritised but action on the best-available evidence is often better than no action at all (Soulé and Wilcox, 1980).

Relevant text was retrieved at the sentence level and all relevant text was included in the classification. Therefore, the fact that study objectives are often restated in the same sentence as the intended conservation outcomes could have contributed to the prevalence of process-related topics. It also could be considered reasonable that each article would contain at least one sentence stating benefits to biodiversity conservation generally. However, these two features are unlikely to sufficiently explain the 68% of articles for which such topics were the highest weighted across all outcome-related sentences. This could have been overcome by using phrases as the unit of analysed text rather than sentences (Zong, Xia and Zhang, 2021). On the one hand, phrases would include less irrelevant text than sentences but may also be missing information required to assess whether the statement is relevant or not. Missing information already presented a challenge in the retrieval of sentences. It should also be noted that the examples of sentences for each outcome topic were chosen to best represent the topic as it was interpreted and do not necessarily represent the variability in sentences.

In combination with existing literature, these findings reinforce that clear communication of intended pathways to action could facilitate the production of research that is more aligned with decision-maker's priorities. When interviewed for Carr Kelman *et al.* (2023) about the actions they take to make their research actionable, 90% of researchers said that they focused on real-world conservation planning and policy outcomes when designing research. Assuming this generalises across science, the results above imply that there is disconnect between the steps that scientists perceive that they take and what is communicated in journal articles. It could be that a pathway to action was clearly-defined but not communicated in journal articles. However, the idea that conservation science outputs are still misaligned with conservation planning and policy priorities is relatively commonplace in the literature (e.g. Mazor *et al.*, 2018; Jarvis *et al.*, 2020; Buxton *et al.*, 2021). By publishing clear intended pathways to action, not only would researchers be prompted to complete this process thoroughly, but it would allow the methods to be scrutinised relative to the intended outcomes and reveal mismatches between researchers' perceptions and the needs of decision-makers.

The lack of association between particular threats and particular actions indicates that unmeasured factors such as biogeographic and socio-political context are more important in determining conservation recommendations than threats in and of themselves. This does not negate the ability of threat maps to inform actions. Most threat maps are produced at a local or sub-national scale (Ridley *et al.*, 2022). As such, it is reasonable to expect that researchers conducting these studies have sufficient understanding of the conservation-relevant context sufficient to suggest candidate conservation actions that could be suitable. Further, Conservation Evidence (www.conservationevidence.com) presents a user-friendly synthesis of evidence on the effectiveness of different conservation actions that have been reported in the literature and which can be filtered by threat and utilised in this manner. The lack of association could also be partly due to the focus of studies on recommending process-based actions (such as Risk Assessment), which are applicable to all threats and interventions. As well as seeking to inform further planning and prioritisation processes, I recommend that threat mapping authors should refine the available intervention options and direct action towards specific areas, an ability that this analysis suggests is currently underutilised.

5.5.2. Extent and manner of stakeholder involvement

Stakeholder involvement in the design and delivery of threat mapping studies was reported in 9% of included articles and covered all stages of the research process from planning, through method development and data collection, to validation of the outputs. This statistic may overlook stakeholder involvement that was either not reported in the article manuscript or was not retrieved by the Boolean search. Text data in acknowledgements was included here but another way to access stakeholder interactions could be to analyse co-author teams and institutional addresses. Further qualitative analyses could also be performed on the extracted sentences (Appendix D.5). Therefore, these results provide a useful baseline for future monitoring of the extent of stakeholder involvement and further study on the manner of stakeholder involvement.

The stakeholder involvement classification model did not identify features, (such as engaging early and consistently, demographic diversity, building trust, and conflict mitigation), that have been associated with the success or failure of stakeholder involvement highlighted by others (Mbaiwa and Stronza, 2011; Mulrennan, Mark and Scott, 2012; Sterling *et al.*, 2017). Based on personal inspection of the stakeholder sentences, it is more likely that this information is not present rather than not detected by the classification model. It could be argued that such information is outside the scope of conservation studies for which analysing the effectiveness of stakeholder involvement was not the objective. This raises a debate about the extent to which researchers should be expected to report the success of stakeholder involvement regardless of the research objectives. More detailed reporting of the lessons learned would allow adaptive improvement of the process, yet higher expectations on reporting may act as a deterrent to engagement. Whether (and where) such conflicting processes balance to generate overall benefit for effective research co-production presents a valuable topic for further analysis and scientific debate.

5.5.3. Evaluating the semi-automated approach

With increasing rates of scientific publishing (Plume and Van Weijen, 2014) there is a great need for automated methods of extracting conservation outcomes and recommended actions from conservation literature (Farrell *et al.*, 2022). In a review of conservation recommendations relevant to climate change McLaughlin *et al.* (2022) opted for a manual approach. The search from a single database returned over 9000 documents and as such, a stratified sample of ~10% were screened (McLaughlin *et al.*, 2022). This presents a large rate of information loss when manual approaches are used due to an unmanageably large literature base.

Here, a vector-space model using either manually-derived queries or a query constructed of modal verbs were shown to be effective in retrieving outcome statements. Manually-derived queries with a low threshold of similarity were shown to be more suitable for building a comprehensive catalogue of outcomes present. Whereas, manually-derived queries with a high threshold of similarity, or modal verbs with a low similarity threshold were suited to reducing the screening time required to retrieve a smaller sample. To test the generalisability of the information retrieval model, further work should apply these queries to new labelled sentences and text extracted from other conservation literature. The training sample used here was also relatively small. Language models for tasks in other fields use thousands if not millions of labelled examples (Gao *et al.*, 2020; Li *et al.*, 2020). Efforts to build such libraries and tools for quickly and easily extracting conservation recommendations could have huge benefits for conservation science in the face of urgent global crisis and a rapidly expanding literature base.

5.6. Conclusions

Difficulty translating science into effective conservation action is not a new issue, yet the increasing rate of scientific publishing means the gap could be expanding faster than it is being closed. Many approaches have been suggested for how to bridge the gap but the extent to which these tools are utilised remains unclear. Here I show that considerable improvements can be made to the communication of the intended outcomes and recommended actions, and extent of stakeholder engagement in threat mapping studies. Such changes are expected to facilitate the alignment of research outputs with planning and policy priorities and ultimately produce more robust and successful outcomes for conservation objectives.

Chapter 6: Discussion

This thesis aimed to understand the state of knowledge on the spatial distribution of threats to the world's species, and to assess how relevant existing threat maps are to the needs of decision-makers in conservation planning and policy. I achieved this by a) systematically searching six peer-reviewed and grey literature sources and screening over 14,000 unique documents, b) thematically characterising the 1,069 relevant threat mapping studies, c) modelling the distribution of research effort relative to conservation need, and d) analysing intended outcome and stakeholder involvement reported in the manuscript text. The rate of publication of threat maps increased substantially over time, and knowledge was unevenly distributed among threats, taxonomic groups, ecological realms, and geographic regions. This analysis provides a strong basis to highlight where considerable amounts of evidence exists, where evidence is needed and how the practices associated with design and delivery of threat mapping research can be improved to better inform action in conservation planning and policy.

The definition of threat mapping was refined here to include only maps that visually present the geographic co-occurrence of threatening human activities and susceptible wild species (Fig 6.1). This differs from previous definitions that also included maps of threatened species (status maps, Myers *et al.*, 2000), and maps of human-pressure irrespective of species presence (pressure maps, Sanderson *et al.*, 2002; Venter *et al.*, 2016a) under the term 'threat mapping' (Tulloch et al., 2015; Ostwald *et al.*, 2021). Status maps, pressure maps, and threat maps differ in the kinds of actions they can inform. Of these, threat maps are considered the most able to inform species threat abatement activities and produce the most refined management priorities (Tulloch et al., 2015; Ostwald *et al.*, 2021).

The variety of terminology used to refer to these maps in the conservation literature has in the past made it difficult to pinpoint relevant research, hindering access to the knowledge contained in this body of literature. A refinement in terminology has, therefore been essential to define explicitly the scope of the systematic (thematic) map of the available literature and all subsequent analyses. The revision in terminology is also useful generally, to identify maps that have the greatest potential utility in planning threat abatement (reduction and mitigation) strategies and make relevant research easier to find within the, otherwise very broad, literature base.

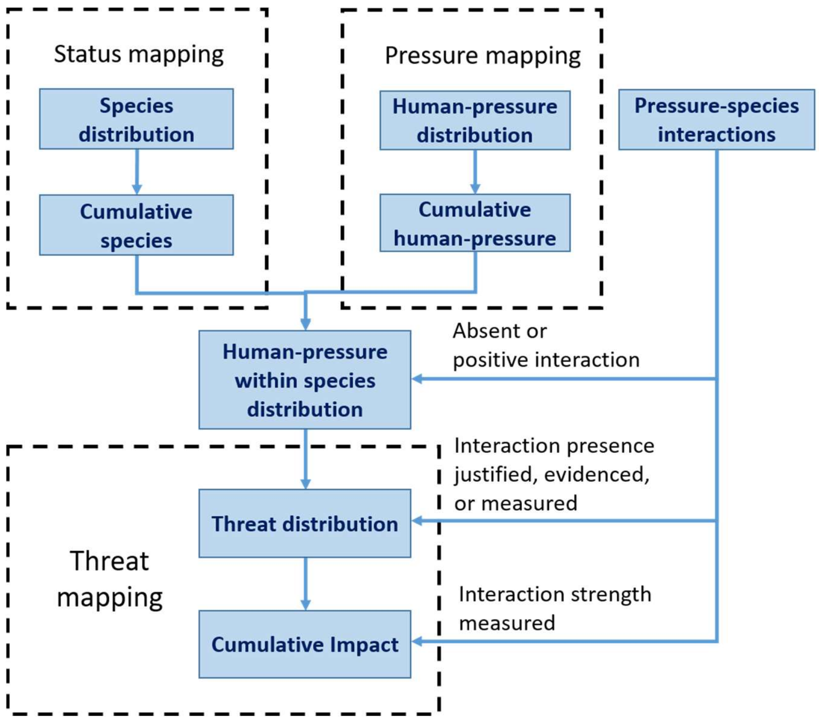

Figure 6.1. A typology of conservation priority mapping methodologies. Adapted from Ostwald et al. (2021).

6.1. Evaluation of approaches

6.1.1. A systematic map of the literature

Through a systematic (thematic) map of the literature mapping threats, I showed that the rate of threat map publication increased substantially 2000 – 2022 (inclusive). The final relevant threat mapping studies (1,069) represented 7.5% of unique articles returned from the systematic search and referred to threats and threat mapping in a variety of ways including those described above. Furthermore, the same search that retrieved 10,646 results from SCOPUS in September 2020 (Chapter 3) now retrieves 15,030 (as of 20.6.23). The combined effects of inconsistent terminology and a rapidly expanding literature base make this information increasingly inaccessible to decision-makers in its raw form.

Evidence synthesis (in this case systematic mapping) allows a large and multi-faceted literature base to be summarised in a way that makes it more accessible to decision-makers (James, Randall and Haddaway, 2016). The summary of the distribution of evidence was presented as a qualitative synthesis and a searchable database of studies complemented by an online interactive web-page. This is not in of itself sufficient to ensure accessibility to decision-makers. The relevant decision-makers also need to know that it exists, where to find it, and have the motivation to use it (Rose *et al.*, 2018). Threat mapping studies that have been published since the search was conducted cover some of the identified gaps (e.g. Guerrero-Pineda *et al*., 2022; Slattery and Fenner 2021; Harfoot *et al.,* 2021; O'Bryan et al., 2022). Therefore, improvements could be made to increase the long-term usefulness of the database, such as regularly updating the process, repeating for studies published in non-English languages, and synthesising the collective knowledge on where threats occur. Nevertheless, it overcomes a major component of the accessibility barrier between threat mapping research and implementation.

6.1.2. Modelling research effort relative to conservation need

This thesis represents one of few attempts to assess bias as the distribution of research effort relative to a measure of conservation need (de Lima, Bird and Barlow, 2011) and is the first attempt to assess bias among threats. For 75% of country-threat combinations threat mapping research effort (mammals and birds only) was balanced relative to threat abatement potential, despite 45% of countries having no studies at all. This reinforces that the distribution of research effort alone is insufficient to identify priorities for future research.

Country-threat combinations where effort and need were approximately balanced, and where effort exceeded need, may still require more research on threats. Due to the broad scope of the review, multiple studies on one country-threat combination could provide an incomplete evidence base. For example, each study could be either very small in spatial scale, coarse in spatial resolution, cover the same threat sub-classes, or the same bird or mammal species. Relative research effort was also proportional to the total volume of threat mapping literature. Therefore, this approach can only be used to compare the relative distribution of knowledge among country-threat combinations or identify where there is extremely high priority for additional research. It does not show if/where there is a surplus of research effort.

6.1.3. Automated text analysis for conservation research

I demonstrated the potential of text-mining tools for retrieving and analysing information on research practices from the threat mapping literature. Such tools complement evidence synthesis and aid in summarising vast quantities of literature in a transparent and reproducible manner (Farrell *et al.*, 2022). Valuable next steps lie in testing the generalisability of this approach to future threat mapping studies and the conservation literature more broadly.

Here, multiple techniques for sentence text extraction, query development, information retrieval and classification were combined into a novel approach. The individual techniques used at each stage ranged from novel (coherent sentence extraction and validation), through recent modifications of established techniques (seeded LDA topic model), to well-established techniques (vector-space model for information retrieval). The field of text-mining and natural language processing is extensive, multiple techniques exist to solve similar problems and techniques are advancing rapidly (Hirschberg and Manning, 2015; McClure *et al.*, 2020; Farrell *et al.*, 2022). Therefore, techniques undoubtedly exist that would improve the performance of this approach given the skills and time to develop them. However, language models used for tasks in other fields use thousands if not millions of labelled examples (Gao *et al.*, 2020; Li *et al.*, 2020). As the main objective here was to minimise the manual workload required to extract a sample of relevant statements, the labelled training sample was relatively small. Therefore, there would be great benefit in pre-training a language model for the retrieval of conservation outcomes and recommended actions that could then be applied to any sub-set of conservation research.

6.2. Priorities for future threat mapping research

The results presented provide a valuable resource for guiding the design of future threat mapping research at any spatial scale as well as highlighting specific priority areas for future research attention. These cover: specific knowledge gaps to be filled, practices to bridge the science-implementation gap and attitudinal changes in the way some threats are viewed.

Due to the broad scope of threat mapping literature, this thesis revealed many intriguing patterns at a variety of scales that could benefit from further investigation. However, the following eight priorities have been chosen due to their high potential contribution to reducing global species extinction risk and their applicability across spatial scales. It should be emphasised that a need for information in these areas does not negate need in others. The search for literature was also performed in September 2020 and, as noted in Section 6.1.1 above, other relevant threat mapping studies have been published since (e.g. Guerrero-Pineda *et al*., 2022; Slattery and Fenner, 2021). Especially where there are gaps in particular geographic areas, this information can also be supplemented with global-scale analyses.

6.2.1. Threats to marine and freshwater systems

The lack of threat maps of marine and freshwater realm (relative to terrestrial), mirrors conservation literature more broadly (Amis *et al.*, 2009; Abell and Harrison, 2020; Hughes *et al.*, 2021; Samplonius *et al.*, 2021). Freshwater systems in particular, are disproportionately diverse given the area that they occupy (Strayer and Dudgeon, 2010), and new species have undergone the greatest population declines of any ecological realm (Almond, Grooten and Peterson, 2020). The important regulatory and provisioning services that marine and freshwater ecosystems provide (Díaz *et al.*, 2019; Kaval, 2019), makes it evermore imperative to understand where and how human activities threaten species in these realms.

Of the threats mapped in the marine realm found in this study, direct exploitation and shipping accounted for the vast majority, yet Colloca *et al.* (2019) showed that most of the top threats to marine ecosystems were of land-based origin. Estimates vary on how much of total cumulative impact is attributed by land-based threats (Ban, Alidina and Ardron, 2010; Murray, Ma and Fuller, 2015). Nevertheless, there is a considerable body of literature on land-based threats to marine systems (Halpern *et al.*, 2009a; Brown *et al.*, 2019) that was not reflected in the threat mapping literature.

Land-based threats are often geographically distanced from the population that they impact; a challenge that affects threat identification and abatement (reduction and mitigation) in both marine and freshwater realms. Threat maps of freshwater systems were distributed more evenly among different threats and several studies were found that successfully mapped the effect of a threat (e.g. dams) on spatially disparate populations (Gargan *et al.*, 2011; Liermann *et al.*, 2012; Carvajal-Quintero *et al.*, 2017; Barbarossa *et al.*, 2020). This could be because the distances between threat source and site of impact can be larger, and the pathway from threat to impact less predictable, in marine systems than in freshwater. Regardless, more studies that map land-based threats to marine ecosystems would facilitate planning of both threat reduction and mitigation interventions of high value to conserving species.

6.2.2. Threats to plants

There is a major lack of information on threats to plants in comparison with animals (particularly vertebrates). I found that plant threat maps tended to be less numerous and less taxonomically specific. One-quarter of threat mapping studies mapped threats to plant species, of which just over half measured plant population presence as the presence of a habitat or land-cover class defined by the presence of plants (e.g. forest or vegetation). This reflects the bias towards animals observed in conservation more generally (Balding and Williams, 2016; Darbyshire *et al.*, 2019). Only 15% of plants have been assessed by the IUCN Red List in comparison with 81% of vertebrates (IUCN Red List, 2022), despite extinction risk among plant species predicted to be higher than among mammals or birds (Brummitt *et al.*, 2015; Pelletier *et al.*, 2018; Nic Lughadha *et al.*, 2020; IUCN Red List, 2022). It is widely perceived that humans have an innate affinity for vertebrates (particularly mammals) over plants (Lindemann-Matthies, 2005). However, more recent evidence suggests that the bias is cultural rather than innately biological (Balding and Williams, 2016). It certainly doesn’t help that in discussions on threats (e.g. deforestation) the primary concerns are often loss of habitat for animals or loss of material services and carbon stocks for humans, with direct threats to plant species rarely considered (Hoang and Kanemoto, 2021; Ritchie and Roser, 2021). Nevertheless, my findings reinforce the need for more overall, and more taxonomically specific, evidence on threats to plants and posit that the utilitarian value of plants has hindered that before now.

6.2.3. Geographical bias

The geographic bias in ecology and conservation towards studying Europe and North America is well-evidenced (de Lima, Bird and Barlow, 2011; Trimble and van Aarde, 2012; Di Marco *et al.*, 2017; Hughes *et al.*, 2021) and reflected in the threat mapping literature. This trend is also observed in studies of the science-implementation gap, about which considerably less is known in Asia, Africa, and South America (Klütsch and Ferreira, 2021). Solutions to conservation and science-implementation challenges that are largely based on a literature-base that is geographically biased are also likely to overlook contextual variation in the suitability of solutions. Such contextual variation may include different human needs, cultures and values, sustainable development challenges and priorities, and technological, institutional, and other capacity constraints. Therefore, there is a need to fill geographic knowledge gaps, not only for the understanding of threats but for understanding how to improve the translation of knowledge into effective conservation decisions.

6.2.4. Agriculture & Aquaculture and Biological Resource Use in the tropics

A lack of evidence does not always represent a neglected need. When conservation need (threat abatement potential) was taken into account, 75% of country-threat combinations had proportionate levels of threat mapping research effort. However, filling the shortfall in research effort on Agriculture & Aquaculture (hereafter simply agriculture), and Biological Resource Use (i.e direct exploitation) in tropical areas of the Americas, Asia, and Madagascar was found to have the greatest potential benefit for informing actions to reduce global species extinction risk. Therefore, further research in these areas is highly recommended.

The urgency of addressing the threat to species of agriculture has been highlighted by many (e.g. Perrings and Halkos, 2015; Ortiz and Torres, 2019; Ahmad *et al.*, 2020) and received the overall highest levels of threat mapping research effort of any threat group globally. However, this research attention is not distributed proportionately to threat abatement potential. In countries where actions to reduce this threat have among the greatest potential to reducing species extinction risk (Mair *et al.*, 2021) there was a significant shortfall in research effort. In particular for agriculture in Colombia, the exceptional shortfall in relative research effort is likely due to a combination of a recent history of conflict and a rapid post-conflict expansion in agricultural activity (Vargas *et al.*, 2015; Murillo-Sandoval *et al.*, 2021; Vanegas-Cubillos *et al.*, 2022; Guerrero-Pineda et al., 2022).

Conversely, Biological Resource Use in Indonesia also represented a shortfall in research effort relative to need, despite receiving among the highest overall levels of research output. This demonstrates the extremely high threat abatement potential of actions to reduce biological resource use in Indonesia. Within Indonesia, there is a recently-initiated and ongoing transfer from a state-managed to a community-managed forestry system, the effects of which are now beginning to be realised (Kraus *et al.*, 2021; Gunawan *et al.*, 2022). Therefore, Indonesia presents a critical opportunity to synthesise the available evidence, monitor the effects of the transition in management, and work collaboratively with communities to sustainably manage their common resources and protect its biodiversity.

The threat of Biological Resource Use is another major threat to biodiversity that receives a lot of research attention globally but for which threat mapping research is distributed unevenly among the geographic regions affected by it. Here, particular shortfalls were reported in Mexico, Madagascar, Indonesia, Colombia, Brazil, and the Philippines, whereas most countries in sub-Saharan Africa received disproportionately high levels of research effort relative to threat abatement potential, species richness, and land area. There are reports on how to manage wild meat harvesting sustainably and other non-spatial syntheses that cover some of these lesser-studied regions (e.g. Coad et al., 2019; Ingram et al., 2021). Although new threat maps have been published in these areas (e.g Restrepo-Cardona et al., 2022), it is not obvious that there has been a major change to the distribution of research effort since the search was conducted. For example, a database aiming to compile evidence of wild meat harvesting, consumption, and trade is currently limited to seven countries in sub-Saharan Africa (Willis et al., 2022).

6.2.5. Map multiple threats

The majority of species and ecosystems are impacted by more than one threat (Halpern et al., 2008; Maxwell *et al.*, 2016; Hogue and Breon, 2022), yet I found that 60% of threat mapping studies mapped a single threat, and where multiple threats were observed they tended to be mapped separately. It is also worth reiterating that threat maps here could include, but were not restricted to, studies that mapped the magnitude of impact. Many of the studies found that mapped multiple threats did not attempt to measure the impact of those threats on species or calculate the cumulative impact. Studies that map the overlap of multiple threats are considered cumulative threat maps (e.g. Gonzalez-Suarez, Gomez and Revilla, 2013; Pierre *et al.*, 2018; Walston and Hartmann, 2018), rather than cumulative impact maps that assess the overall impact of multiple threats (Fig 5.1, e.g. Underwood, Francis and Gerber, 2011). Though terrestrial examples of cumulative impact mapping do exist (Bellard, Leclerc and Courchamp, 2015; Herve, Albert and Bondeau, 2016), the approach has primarily focused on marine systems (e.g. Halpern et al., 2008; Halpern *et al.*, 2009b; Halpern and Fujita, 2013; Halpern *et al.*, 2015; Lieske *et al.*, 2020; Singh *et al.*, 2021). Therefore, the bias towards terrestrial threat mapping likely contributed to the relative lack of cumulative threat maps observed.

In cumulative impact mapping, the interactions between threatening processes become more important. Interactions occur among threats (here, human activities and human-initiated processes), among stressors (here, the ecological change/mechanism that delivers impact to the biological entity), and between threats and stressors. Depending on the types of interactions present (e.g. synergistic or antagonistic, Brown *et al.*, 2014), taking action to reduce one threat can have overall positive or negative effects on the target population (Crain, Kroeker and Halpern, 2008). Where and how non-additive interactions occur is often unpredictable (Stockbridge et al 2020). Under incomplete data on interactions, it is important to weigh-up the potential risk of action under different interaction scenarios, the likelihood of each of those interaction scenarios being true, the time required to generate sufficient data to understand the nature of interactions, and the risk of inaction during that time.

6.2.6. Seek to inform specific actions as well as planning processes

Threat mapping has the potential to be used to inform conservation practice and policy interventions much more effectively than at present. Threat mapping studies predominantly reported the intention to inform conservation planning processes, tools, and techniques, with specific actions (particularly policy and societal actions) being less frequent. This also indicates that the full pathway from research output to action is not fully defined. In conservation planning processes, such as systematic conservation planning and cost-benefit analysis, initial candidate actions are required (Margules and Pressey, 2000; Tulloch et al., 2015). Therefore, threat mapping studies have the ability to: identify what threats are occurring where, suggest candidate actions, direct actions to where they are most needed, and reject any candidate actions that are unlikely to be effective given the specific socio-ecological context of the study. In the majority of cases, the threats being investigated are known during the planning stages of an investigation, therefore so too are potential interventions to those threats. Conservationevidence.org provides a useful resource for finding evidence on the effectives of conservation interventions and could be utilised in this manner (Sutherland *et al.*, 2018; Sutherland *et al.*, 2020b). Designing a threat mapping study with candidate interventions in mind would pre-empt mismatches between the design of the study and the actions it is intending to inform and similarly make the outputs less likely to be irrelevant (e.g. in spatial scale) to decisions regarding those interventions.

6.2.7. Involve stakeholders in threat mapping design and delivery

Early engagement of relevant stakeholders is a highly recommended solution to the knowledge-implementation gap (Cvitanovic *et al.*, 2015; Cvitanovic *et al.*, 2021), yet stakeholder engagement in threat mapping studies was reported infrequently. Stakeholders here include any individual, group or institution that can affect or is affected by conservation decisions. These include but are not limited to: relevant experts, governing bodies, and any person living or working in relevant areas or industries (e.g. conservation practitioners). Stakeholder engagement can enhance the long-term success of conservation projects by increasing cooperation and motivation for behaviour change through fostering a sense of empowerment, ownership, and mutual trust (Hyman *et al.*, 2022; LeFlore *et al.*, 2022). Therefore, I recommend increasing the rate of well-planned stakeholder engagement in threat mapping research, monitoring the rate of engagement, and monitoring the effectiveness of engagement. This is likely to result in research outputs that are more relevant to stakeholders' needs, build positive long-term relationships between scientists and stakeholder groups, and ultimately result in more resilient conservation decisions.

6.2.8. Treat climate change as a current, rather than future, threat

Climate change is predicted to become a major threat to species (Warren *et al.*, 2013; Urban, 2015), yet relatively few studies mapped the observed threat of climate change. Anecdotally, based on the titles, abstracts and full-texts excluded in the screening stages, if maps of predicted or future threats were included here, climate change would be much more prevalent. Early reported effects of climate-change induced ecological changes included phenology, range shifts, community shifts, trophic interactions, and susceptibility to other threats (Walther *et al.*, 2002; Parmesan and Yohe, 2003). More recently, observed impacts have progressed to mass mortality events in multiple animal and plant taxa, loss of entire populations, and some species extinctions (Almond, Grooten and Peterson, 2020; Parmesan *et al.*, 2022). This highlights that climate change is a threat to species now, as opposed to a threat that will become important in the future. More spatial analysis of where climate impacts on species have already occurred will be crucial in the development of interventions designed to mitigate that impact (Pearce-Higgins *et al.*, 2022).

6.3. Implications for conservation policy and practice

These outputs can aid the implementation of the Kunming-Montreal Global Biodiversity Framework (CBD, 2022c) through increased accessibility to evidence on where threats directly impact wild animal and plant species (Table 6.1). Aside from highlighting where there are high-priority gaps for more research, this suite of analyses highlights that there is a considerable amount of evidence of direct relevance to the implementation of the framework. At any spatial-scale this evidence could be synthesised or used directly to inform biodiversity-inclusive spatial planning and prioritisation of international resources. Policy-makers and conservation practitioners at local and national-scales can also use the outputs presented to find evidence on threats to species that meets their requirements (such as the interactive database of studies, Chapter 3).

Of particular note is the threat of Linear Infrastructure (e.g. roads, railroads, and utility lines), which was among the highest studied threats but is not specifically mentioned in the Global Biodiversity Framework. There is considerable agreement among studies on the threat of linear infrastructure about the various impact it has on species (Grilo *et al.*, 2021; Pinto, Clevenger and Grilo, 2020; Krief *et al.*, 2020; Sloan *et al.*, 2019), despite being reported as a major threat in species IUCN Red List Assessments relatively rarely (Maxwell *et al*., 2019). In the long term, this presents potential justification to account for the impact of Linear Infrastructure in future revisions of the framework. In the short term, it could be used to encourage countries to report explicitly on linear infrastructure under other targets related to spatial planning, restoration, and reducing extinction risk. The database of literature presented here could be utilised to investigate that justification further and aid implementation if such a change were adopted

6.4. Conclusion

In conclusion, the increasing urgency of the ecological crisis and critical role of threat abatement in halting species extinctions means that it has never been more important to consolidate what is known about where human activities directly impact wild species. Here, I present a review of the distribution of threat mapping literature, a quantitative analysis of the knowledge gaps relative to threat abatement potential (conservation need), and a novel semi-automated assessment of the use of research practices that facilitate the relevance of outputs to the needs of conservation decision-makers. The diverse and multi-faceted nature of the threat mapping literature resulted in a rich synthesis, containing useful information for conservation planning, policy and future research across spatial scales. In particular the suite of analyses identified eight overarching priorities for threat mapping research going forward: threats to marine and freshwater systems, threats to plants, geographic bias, agriculture, aquaculture and biological resource use in the tropics, multiple threats, seeking to inform direct actions as well as planning processes, involving stakeholders in the design and delivery, and treating climate change as a current, rather than future threat. Filling these gaps will aid the successful implementation of the Kunming-Montreal Global Biodiversity Framework and help to prevent further species extinctions.

Table 6.1. How relevant targets from the Kunming-Montreal global Biodiversity Framework (CBD, 2022c) are addressed in the threat mapping literature and the findings of this thesis can inform implementation of the framework.

	Target summary	Findings relevant to implementation of the Global Biodiversity Framework
1	All areas under participatory, integrated and biodiversity-inclusive spatial planning to bring the loss of areas of high biodiversity importance close to zero by 2030	The database of threat mapping studies can directly inform biodiversity-inclusive spatial planning at a variety of scales
2	30% of degraded terrestrial, inland water, coastal, and marine areas are restored by 2030	The database of studies can be used to effectively abate and monitor incursion or spread of human-driven threats as part of a restoration plan.
3	30% of terrestrial, inland water, coastal, and marine areas are effectively conserved and managed by 2030	The database of threat mapping studies can be used to abate and monitor incursion or spread of human-driven threats as part of a reserve management plan.
4	Urgent management actions to halt human-induced extinction of known threatened species and significantly reduce extinction risk	These results highlighted where actions to abate threats could have the greatest contribution to reducing species extinction risk and where among these there is a severe lack of information versus where there may be sufficient for evidence-based management actions.
5	Use, harvesting and trade of wild species is sustainable, safe and legal, minimizing impacts on non-target species and reducing risk of pathogen spill over.	Biological Resource Use (BRU) in Mexico, Madagascar, Indonesia, Colombia, Brazil and the Philippines had very low numbers of studies relative to the high contribution that addressing this threat in these places could make to reducing species extinction risk. BRU in Indonesia was among the most highly studied threats in any location. The collective findings of these 15 studies could yield powerful insights for managing the sustainable use of wild species in Indonesia.
6	Eliminate, minimize, reduce, and or mitigate the impacts of invasive alien species	Alien invasive species were the subject of overall the most studies globally at any spatial scale, somewhat driven by North America, Europe, Australia and the terrestrial realm. Though studies on invasive species were relatively numerous across all continents, when compared to threat abatement potential, research effort was relatively low for most countries in Africa, Asia, Eastern Europe, and western areas of South America. 9% of articles in a 550 article sample recommended invasive species control.
7	Reduce pollution risks and the negative impact of pollution from all sources by 2030	There is a need for more evidence on the threat of pollution across most geographic areas and ecological realms (terrestrial, freshwater, and marine). The criteria for inclusion of threat

		mapping studies may have resulted in the exclusion of studies related to pollution where the impacts to species are geographically separated from the anthropogenic source activity.
8	Minimize the impact of climate change and ocean acidification on biodiversity and increase its resilience through mitigation adaptation and disaster risk reduction	Less threat mapping studies were found for the threat of climate change than other threats. Many studies on climate change were excluded due to mapping a future rather than observed threat distribution. More information is needed on where impacts of climate change on species have already been observed and where species exist at the edge or within a severely restricted climatic niche.
9	Management and use of wild species is sustainable	The database of studies can be used to identify areas where natural resource extraction may not be conducted sustainably.
10	Ensure that areas under agriculture aquaculture, fisheries and forestry are managed sustainably	The database of studies can be used to identify areas where agriculture, aquaculture, fisheries, and forestry are not currently conducted sustainably. Agriculture and aquaculture was overall the most studied threat in the threat mapping literature globally at any spatial scale. However, when compared to threat abatement potential there was a relative shortfall in knowledge for the tropical areas of the Americas, Asia, and Madagascar.
21	Ensure that the best available data, information and knowledge are accessible to decision makers, practitioners and the public	The online searchable database of studies overcomes barriers hindering the accessibility of relevant threat mapping studies to decision-makers and provides a user-friendly interface for easier communication with decision makers, practitioners and the public. Chapter 5 provides a protocol for quickly extracting recommended actions from the threat mapping literature for easier assimilation by decision-makers and practitioners.

Appendix A: supplementary material to chapter 2

[see additional files]

** These files are available in the thesis supplementary folder or to download from the journal website: https://environmentalevidencejournal.biomedcentral.com/articles/10.1186/s13750-020-00206-8

Appendix A.1: Eligible population and outcome: Examples of pre-defined areas that are considered eligible proxies for population, and examples of eligible threats

Appendix A.2: Search strategy: Details of search strategy development including the test-list of benchmark articles, identification of keywords, development and testing of search strings, and specifics of the final search for each database used.

Appendix A.3: Search testing specifics: Details of every search attempted in the process of search string development in SCOPUS

Appendix A.4: Data Coding Tool: The spreadsheet used for coding of meta-data, including descriptions of the topography and definitions to be used by reviewers.

Appendix A.5: completed ROSES Form

Appendix B: supplementary material to chapter 3

[see additional files]

** These files are available in the thesis supplementary folder or to download from the journal website:
https://environmentalevidencejournal.biomedcentral.com/articles/10.1186/s13750-022-00279-7

Appendix B.1: Examples of threat maps: Example threat maps from some of the included threat mapping articles.

Appendix B.2: Supplementary search details: Specifics of how each database and organisational websites were searched

Appendix B.3: Supplementary eligibility information: Further details of what priority areas were considered a valid proxy for species presence within this study and examples of **articles that challenged the eligibility criteria and how they were treated.**

Appendix B.4: Searchable database of studies: A multiple page workbook containing the coding tool and data collected per article, bibliography, term definitions, disaggregated dataset, and article searching tool.

Appendix B.5: Excluded full-texts: Bibliographic details of all studies that passed abstract screening but were not included in the final systematic map and the reasons why they were excluded.

Appendix B.6: Geographic distribution tables: Details of the number of relevant threat mapping articles found for each land area and marine territory.

Appendix B.7: Completed ROSES Form

Appendix C: supplementary material to chapter 4

Appendix C.1: Manually filled country meta-data: [see additional files]

** This file is available in the thesis supplementary folder

Appendix C.2: Model validation: Figures used to validate the negative binomial generalised linear model.

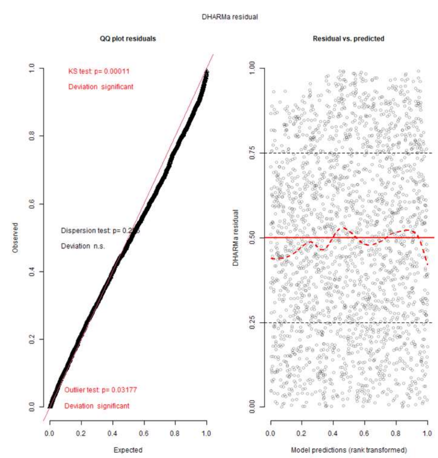

Figure C.2.1. DHARMA validation plots for the final model to predict the number of threat mapping studies per country per threat.

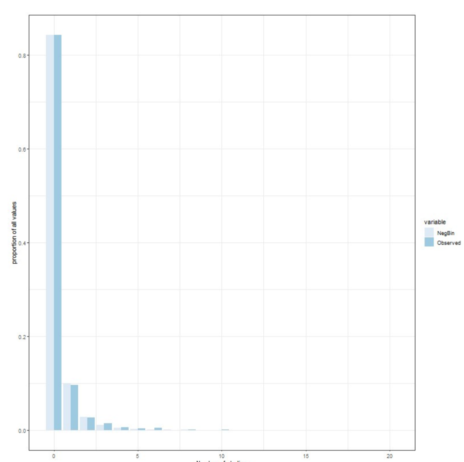

Figure C.2.2. The distribution of study counts compared between a) the observed data and b) data predicted from the final negative binomial generalised linear model with random intercept (NegBin).

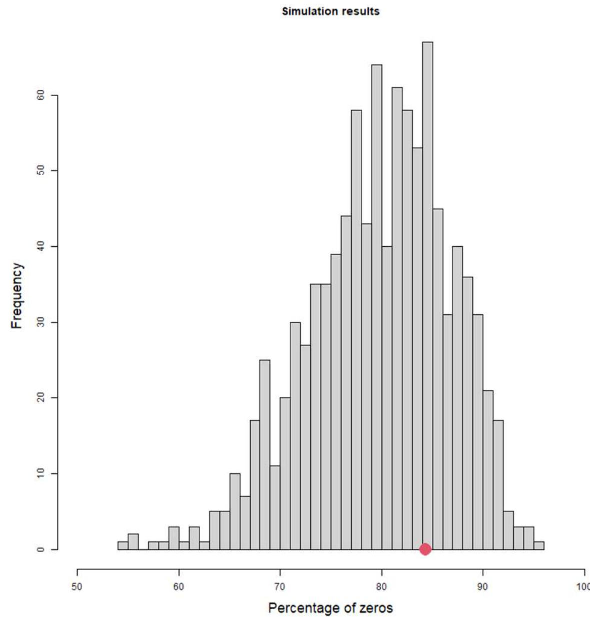

Figure C.2.3. The percentage of zeros among 1000 datasets simulated from the final negative binomial generalised linear model with mixed effects. The red dot indicates the percentage of zeros in the observed data.

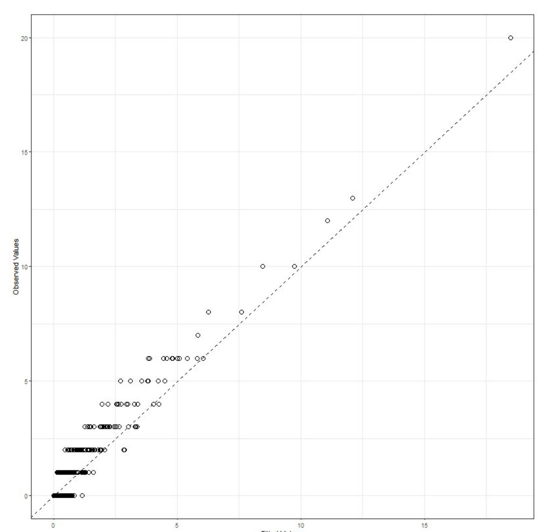

Figure C.2.4. The relationship between observed numbers of studies and the values predicted from the generalised linear model with negative binomial error structure.

Appendix C.3: Supplementary results: Distribution of relative research effort among threats and random effect of country predicted from the negative binomial generalised linear model.

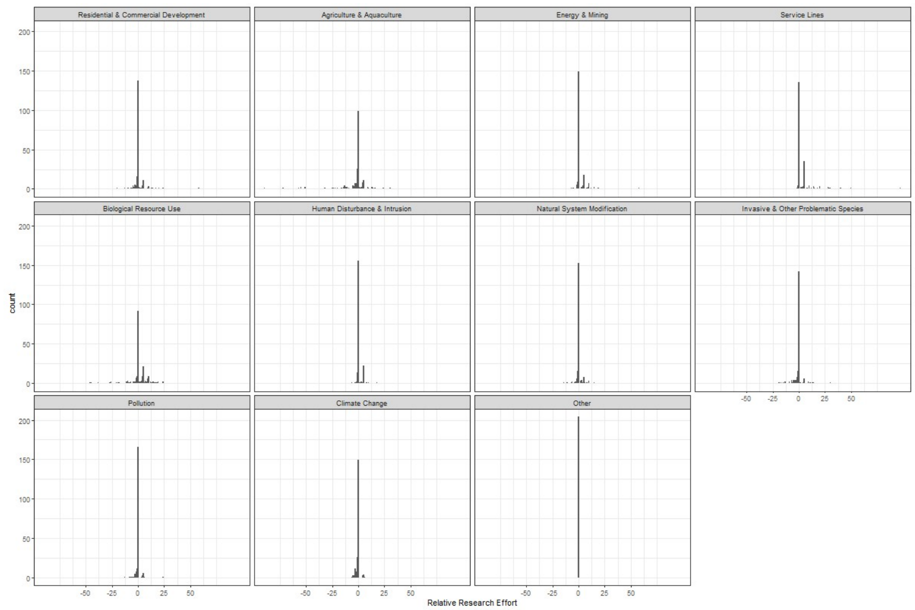

Figure C.3.1. The distribution of relative research effort (RRE) among threats

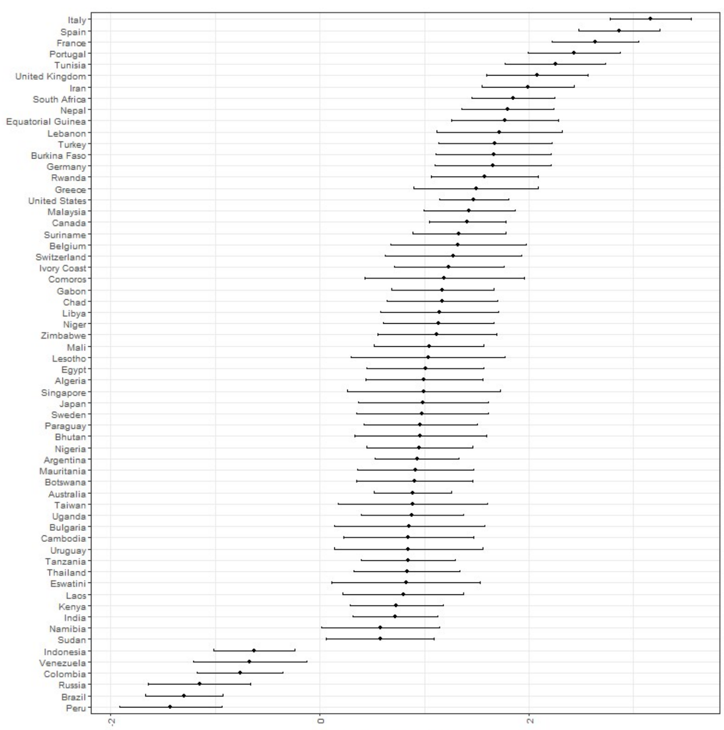

Figure C.3.2. Conditional Mean intercept from the negative binomial generalised linear model for each country for which 95% confidence intervals did not overlap zero.

Appendix D: supplementary material to chapter 5

Appendix D.1: The five candidate queries: lists of terms (word) that made up each of the five candidate queries and the final query used.

conservation	involve	decisions	locate	safeguard	quantify	inexpensive
biodiversity	key	dedicate	make	safety	researchers	install
species	likely	delineate	manage	scenarios	scenario	interest
risk	monitoring	designing	meaningful	secure	tool	invaluable
corridor	need	detect	measure	securing	understanding	investment
priority	network	detection	mitigate	seriously	ability	involved
assessment	option	develop	model	setting	account	jeopardize
management	park	distribute	modify	shape	acquire	lending
analysis	program	drastic	motivation	significance	advise	maintain
change	protect	education	observe	significant	afford	major
barriers	step	effective	outcome	stewardship	allocate	making
important	strategy	effectively	overcome	stopping	allocating	maximize
planning	support	efficient	patrol	strategic	alternative	micro-siting
research	accomplish	elevate	perception	strengthen	assure	minimize
action	activity	enable	persistence	stressor	budget	money
capacity	adaptability	enforce	policy	succeed	bypassing	monitor
data	adopt	establish	political	suggest	call	monitored
decision	aichi	estimation	potential	supplement	clarify	participate
effort	allow	evenly	predict	sustainability	clarity	perform
ensure	ambitious	exacerbate	prevent	sustainable	collaboration	policymaker
government	ascertain	expand	preventive	target	communication	possibility
indicator	assess	expertise	prioritization	task	convince	powerful
information	assist	explore	prioritize	understand	creation	preserve
necessary	attention	exposure	programm	unsustainable	criterion	preserving
new	attract	extremely	programme	update	declare	prevention
plan	authority	facilitate	project	urgent	decrease	proactive
pressure	avoid	functioning	promote	urgently	deeper	proper
process	balance	give	promotion	value	educate	purpose
protection	benefit	grant	prosecution	may	effectiveness	recognize
provide	broaden	greater	prospects	should	efficiently	remove
restoration	buffer	greatest	provision	can	engage	responsibility
study	campaign	guide	pursue	could	engagement	scheme
useful	campaigns	help	recommend	will	essential	solve
act	care	highest	recover	would	establishment	spending
aim	caution	imperative	recovery	might	evaluate	stakeholder
better	coherent	implement	redd	must	expenditure	stricter
bring	combine	improve	reduce	future	financial	strictly
construction	comprehensive	increase	regime	manager	forbid	success
cost	confer	indispensable	regular	achieve	force	successful
design	confront	initiative	regulate	adaptive	formulation	suitability
determine	connectivity	insight	regulation	appropriate	funding	surveillance
encourage	conserve	interference	release	best	goal	tailor
expansion	consolidate	interventions	render	direct	harmonize	targeting
identification	construct	introduce	require	economic	highly	translate
identify	consume	invest	requirement	incorporate	hinder	usefulness
impact	control	knowledge	reserve	opportunity	implication	valuable
implementation	corruption	lead	resolution	possible	improvement	
importance	crucial	learn	restore	potentially	incorporating	
inform	curb	legislation	retain	practice	incorporation	
	decent	limit	revision	propose		

Table D.1.1. Q1 terms. This query was derived manually from keywords present among sentences labelled as actions.

power	achievement	assign	satisfy	circumvent	constrain	particularly
facility	accomplishment	consign	reassure	aptitude	satisfactory	markedly
capability		allot	embolden	transformative	fair	acutely
utilty	undertake	apportion	empower	resolve	reasonable	exceedingly
inability	inactivity	permit	appeal	rational	sufficient	excessively
incapacity	inaction	license	official	alliance	acceptable	inordinately
competence	inertia	warrant	administration	integrate	adequate	extraudinarily
realise	passivity	authorise	prerogative	discourse	ample	prohibit
realize	idleness	authorize	privilege	tackle	solution	ban
produce	immobility	prefer	stop	preservation	abate	disallow
fulfil	enterprise	course	hamper	save	abatement	proscribe
execute	flexibility	intent	foil	maintenance	commit	preclude
attain	versatility	fitting	inhibit	custody	pledge	criminalise
effectuate	compliance	suitable	avert	custodian	decide	criminalize
fail		evaluation	defend	safeguarding	dictate	intention
forsake	accept	appraisal	refrain	guardianship	extreme	harmony
worth	assume	valuation	bypass	guardian	radical	coordinate
advantage	approve	demand	elude	safekeeping	coach	attune
consequence	embrace	duty	solicit	stabilise	capable	cohere
merit	endorse	toll	obstacle	stabilize	helpful	obligatory
momentous	ratify	levy	hurdle	passageway	operative	prime
complete	urge	tariff	impediment	expense	inspire	prospect
gain	counsel	tax	hindrance	expediture	stimulate	
earn	advocate	taxation	stronger	invention	rouse	
win	prescribe	aid	improved	conception	administer	
obtain	teach	collaborate	progressing	vital	certify	
procure	influence	cooperate	recovering	pressing	guarantee	
reap	instruct	expedite	healthier	restrain	requisite	
possess	sustain	abet	deliver	contain	indispensible	
work	offer	boost	income	restrict	equally	
serve	supply	ease	allocation	moderate	regularly	
operate	impart	reinforce	finances	suppress	uniformly	
function	aspire	condone	funds	repress	identically	
performance	seek	persuade	evade	impede	exceptionally	

Table D.1.2. Query 2 additional terms. Query 2 was derived manually from Query 1 and added synonyms.

acknowledge	environmentally	multiscale	substantially	degraded	incentive	regulatory
agenda		nonnatural	successful	deliberate	integral	release
aggregation	exercise	nontarget	surveillance	demonstration	interventions	retain
aid	expertise	optimal	sustainably	deplet	iterative	round
algorithm	extinct	pathway	tackle	deserve	kba	severely
analytical	firefly	phase	technical	desirable	loca	simultaneous
arctic	flexible	platform	unsustainable	devise	managing	sos
arise	focuss	policymaker	utmost	duce	mandate	sprfmo
association	gom	preference	vital	dugong	marxan	stability
authority	guidance	prevention	walnut	economically	medium	straightforward
awareness	harbour	prioritise	want	education	micro	stranding
away	hydrocarbon	purpose	wilderness	efficiently	minimizing	subsequently
behaviour	identifying	question	active	eliminate	mitiga	substitute
brazilian	improved	recover	alleviate	enforcing	mon	swafr
broadly	incorporation	reducing	always	engage	necessarily	techniques
budget	interconnect	refin	anticipate	fast	operational	temperatur
canadian	interface	refugia	byra	fencing	participation	thorough
connect	intervention	rely	causative	formation	pas	transfer
conserva	landuse	remove	channel	formulate	patrol	translate
conservationist	largest	repeat	choose	formulation	policing	ultimate
creation	likewise	responsibility	clarify	friendly	preferred	underpin
descriptor	making	responsible	collaboration	goods	prioritizing	underway
disentangle	meaningful	roi	commit	guarantee	private	urgency
eco	meeting	scape	company	hazardous	proach	urgently
ecologic	metic	seascape	concession	heterogeneous	proactive	waterbird
elaborate	minimal	soon	consequent	immediately	publicly	zonation
encroachment	minimum	spend	containment	immense	quick	
engagement	motivation	subpopulation	coordination	imply	regeneration	

Table D.1.3. Query 3. Algorithm-derived query with no multiplier.

acknowledge	flexible	recover	channel	goods	proactive
agenda	focuss	reducing	choose	guarantee	publicly
aggregation	gom	refin	clarify	hazardous	quick
aid	guidance	refugia	collaboration	heterogeneous	regeneration
algorithm	harbour	remove	commit	immediately	regulatory
analytical	hydrocarbon	responsibility	company	immense	release
arctic	identifying	responsible	concession	imply	retain
association	improved	roi	consequent	incentive	round
authority	interconnect	scape	containment	integral	severely
awareness	interface	seascape	coordination	interventions	simultaneous
away	landuse	soon	degraded	iterative	sos
behaviour	largest	spend	deliberate	kba	sprfmo
brazilian	likewise	subpopulation	demonstration	loca	stability
broadly	making	substantially	deplet	managing	straightforward
budget	meaningful	successful	deserve	mandate	stranding
canadian	meeting	surveillance	desirable	marxan	subsequently
connect	metic	sustainably	devise	medium	substitute
conserva	minimal	tackle	duce	micro	swafr
creation	minimum	technical	dugong	minimizing	techniques
descriptor	motivation	unsustainable	economically	mitiga	temperatur
disentangle	multiscale	utmost	education	mon	thorough
eco	nonnatural	vital	efficiently	necessarily	transfer
ecologic	nontarget	walnut	eliminate	operational	translate
elaborate	optimal	want	enforcing	participation	ultimate
encroachment	pathway	wilderness	engage	pas	underpin
engagement	phase	active	fast	patrol	underway
environmentally	platform	alleviate	fencing	policing	urgency
exercise	policymaker	always	formation	preferred	urgently
expertise	prevention	anticipate	formulate	prioritizing	waterbird
extinct	prioritise	byra	formulation	private	zonation
firefly	purpose	causative	friendly	proach	

Table D.1.4. Query 4. Algorithm-derived query with multiplier.

would
will
may
should
could
must
can
Might

Table D.1.5. Query 5. Modal verbs.

Appendix D.2: Term conversion table: list of terms that were changed in pre-processing text for the seeded classification of conservation outcomes and recommended actions.

from	to
lands	land
protect	protection
conserve	conservation
conserva	conservation
plan	planning
habitats	habitat
watershed	water
watersh	water
manage	management
manager	management
designing	design
prioritise	prioritization
prioritize	prioritization
mitigate	mitigation
bycatch	harvest
catch	harvest
hunt	harvest
hunting	harvest
fishing	harvest
logging	harvest
collect	harvest
collection	harvest
recover	recovery
campaigns	campaign
invest	investment
policymaker	policy
regulate	regulation
methodology	method
methods	method
application	apply
fund	funding
detect	detection

Table D.2. Terms that were changed in pre-processing text for the seeded classification of conservation outcomes and recommended actions and what they were changed to.

Appendix D.3: Classification of outcome topics and themes: Interpretation of outcome/action topics with examples of studies and sample sentences

*Table D.3.1. Statements of recommended actions and intended outcomes from threat mapping studies classified using a partially-seeded latent Dirichlet allocation (LDA) topic model. *Seed words – prior topic-term associations that were specified. Examples are some retrieved sentences from studies for which the topic was among the five highest weighted topics. Documents where the topic was the highest weighted were used where possible. IUCN framework derived topics are numerically code in exact reference to the framework.*

Source (Theme)	Topic		Terms	Examples	References
Additional Seeded (Conservation Planning)	1	Biodiversity conservation planning	biodiversity*; conservation*; planning*; action*; practice*	1 - "Understanding of threats and population trends is vital for conservation planning to direct appropriate conservation actions and resources." 2- "we identify global human impacts on threatened vertebrates, hotspots of impacted species richness and also 'coolspots' that act as refuges from threats providing essential information for conservation planning and action."	1 - Abram et al 2015 2-Allan et al 2019
IUCN (Protection of species, sites, or resources)	2	IUCN_1: Land or water protection	area*; protection*; land*; park*; safeguard*	1 - "If natural resource managers and local governments are to make informed decisions about land use policy in the face of change they must be apprised of the geographic and temporal distribution of land use and land cover change in the GYE and the implications for ecosystem dynamics and native species." 2- "targets for the amount of habitat that needs to be protected to safeguard an individual species must be tailored according to the species' range size."	1 - Parmenter et al 2003 2- Pidgeon et al 2015
IUCN (Protection of species, sites, or resources)	3	IUCN_1.1: Site or area protection	area*; protection*; mpa*; site*; reserve*	1 - "Our spatially detailed and species-specific results may support future national and global conservation agendas including the design of post- protected area targets and strategies." 2- "The results of this project should also be useful for reef managers around the world to identify sites that require aggressive restoration actions or to prioritize the protection of pristine reef areas."	1 - Gallego-Zamorano et al 2020 2- Aubrecht et al 2008
IUCN (Protection of species, sites, or resources)	4	IUCN_1.2: Resource and habitat protection	habitat*; resource*; land*; protection*; water*	1 - "Both the habitat suitability and abundance maps could help decision-makers determine the best means of protecting this species' habitat and can be used as references to reduce or prevent habitat loss and degradation of the Grande Comoro forests." 2- "although our threats analysis is limited to those threats occurring within the economic zone our assessment is a first step in designating spatial locations in the gom where limited conservation resources may be focused to achieve population recovery."	1 - Ibouroi et al 2019 2 - Hart et al 2018
IUCN (Management of species, sites, or resources)	5	IUCN_2: Land or water management	management*; land*; maintain*; site*; water*	1 - "The assessment presented here is the first step of what needs to be a long-term wildlife management process." 2- "The results will help wetland managers to assess the combined effects of the tidal barriers and freshwater releases and improve their management of such wetlands"	1 - Zapata-Ríos et al 2009 2- Yang et al 2019
IUCN (Management of species, sites, or resources)	6	IUCN_2.1: Site or area management	management*; prioritization*; design*; maintain*; msp*	1 - "Assessing the cumulative impacts of multiple commercial fisheries is therefore a critical analysis for guiding the prioritization of marine turtle management and conservation actions." 2- "we aim to understand which management strategies could prevent the extinction of native populations."	1 - Riskas et al 2016 2- Manenti 2014

IUCN (Management of threats)	7	IUCN_2.2: Invasive or problematic species control	species*; control*; invasion*; problem*; alien*	1- "specific aims of our study were to determine the spatial distribution of the main invasive alien plants to predict the potential extent of invasive alien plants and to assist decision-makers and nature reserve managers in controlling the spread of invasive alien plants on la reunion." 2-"our assessment will inform dog control programs including monitoring education veterinary care and other measures."	1 - Baret et al 2006 2-Callan et al 2020
IUCN (Management of species, sites, or resources)	8	IUCN_2.3: Habitat and natural process restoration	threat*; mitigation*; restoration*; corridor*; buffer*	1 - "the two stepping-stone patches outside the corridor with an area of 75 km2 could potentially be important habitat should efforts be made to create suitable habitat conditions to improve connectivity with the corridor and in the matrix proper." 2- "these monitoring programmes should then inform the development and revision of land use plans both within the corridors and the free membership zone of the national park."	1 - Mohammadi et al 2018 2- Lagabrielle 2009
IUCN (Management of species, sites, or resources)	9	IUCN_3.1: Species Management	management*; species*; plant*; population*; animal*	1 - "we believe that this general methodology can be applied to focus conservation strategies for other species at risk and to guide both population recovery efforts and land use management decisions." 2- "additionally we think the same analysis with other biological groups would be extremely useful for the design of conservation schemes land use policies and rural reform programmes in order to prevent extinctions and to decrease threats to the species in colombia one of the most biodiverse countries in the world."	1 - Boulanger et al 2014 2-Calle-Rendón 2018
IUCN (Management of threats)	10	IUCN_3.1.1: Harvest Management	harvest*; trade*; limit*; sustain*; exploitation*	1 - " finally our results can inform cosewic and sara assessments and recovery strategies for threatened species such as setting bycatch quotas promoting more selective gear improving release practices and identifying core areas for protection." 2-"by highlighting trade in species not assessed by the iucn red list and cites we show the need for relevant data on wildlife exploitation and underlying life history traits population and distribution data which are to be considered essential for policymakers to develop and implement relevant regulations."	1 - Hurley et al 2019 2- Jensen et al 2019
IUCN (Management of threats)	11	IUCN_3.1.3: Limiting population growth	reduce*; population*; control*; limit*; growth*	1 - "finally it is possible to achieve successful mink control providing the strategy adopted is systematic and not occasional as has of ten been the case in the past ." 2-"population control strategies should then consider social components and be integrated with conservation and restoration of native forests and with an appropriate planning of the spatial distribution of planted forests to reduce dog invasion."	1 - Bonesi et al 2007 2- Ribeiro et al 2018
IUCN (Management of species, sites, or resources)	12	IUCN_3.2: Species Recovery	species*; restoration*; recovery*; population*; enhance*	1 - "wetland conservation and restoration policies should be based in comprehensive knowledge about changes in wetland extent and conditions." 2- "although our threats analysis is limited to those threats occurring within the economic zone our assessment is a first step in designating spatial locations in the gom where limited conservation resources may be focused to achieve population recovery."	1 - Patino and Estupinan-Suarez 2016 2- Hart et al 2018
IUCN (Management of species, sites, or resources)	13	IUCN_3.3: Species reintroduction	species*; population*; introduction*; release*; introduce*	1 - "Continued long-term monitoring will provide further insight into how these changes might affect grizzly bears and their habitats." 2- "integrative analyses that incorporate additional environmental data also could help guide implementation of precautionary steps aimed at reducing the likelihood of future introductions."	1 - Schwartz et al 2010 2- Moody et al 2017
IUCN (Law, policy, and people)	14	IUCN_4: Education and Awareness	community*; engagement*; education*; perception*; campaign*	1 - "protected areas are often more effective when local communities are included in decision making and increasing community engagement is likely key to the success of tesso nilo." 2- "we propose this can be achieved by taxonomic and spatial prioritisation of research and management examining potential synergisms between dogs and other threatening processes strategic engagement with animal welfare and human health campaigns community engagement and education and mitigating anthropogenic effects such as resource subsidies."	1 - Poos et al 2019 2- Doherty et al 2017

IUCN (Law, policy, and people)	15	IUCN_5:Legislation policy and regulation	policy*; government*; regulation*; legislation*; rights*	1 - "focused efforts are needed to develop policies and plans with national spirit to adopt adaptive measures for biodiversity and forestry sector to withstand the present and possible future impacts of climate change." 2- "the results from this study emphasize the need for implementation of public policies aimed to reduce deforestation and wildland fires in the state thus ensuring the conservation of the amazon rainforest and its biodiversity."	1 - Baig and Aldosari 2012 2-Zhai et al 2012
IUCN (Law, policy, and people)	16	IUCN_5.4:Compliance and enforcement	detection*; regulation*; patrol*; surveillance*; policing*	1 - "to this aim the results of our study can be helpful as they allow focusing surveillance actions to the areas with the highest poaching potential ." 2- "combined these insights will aid patrol strategy decisions and improve patrol ability to inhibit poaching opportunities which will in turn provide spillover benefits into surrounding areas ."	1-Ferreguetti et al 2018 2-Thialt et al 2020
IUCN (Law, policy, and people)	17	IUCN_6:Livelihood economic and other incentives	investment*; allocate*; scheme*; livelihood*; incentive*	1 - "Our study indicated that most turtle nesting areas across all species were on private land and conservation there will require engagement with communities public support and most likely incentives to achieve the behavioral changes necessary to mitigate threats ." 2-"looking forward meeting the globally agreed targets of preventing extinction and improving species' conservation status will require focused conservation investment in countries with larger shares of responsibility for global biodiversity."	1-Fuentes et al 2016 2- Rodrigues et al 2012
IUCN (Law, policy, and people)	18	IUCN_7:Capacity building	development*; network*; capacity*; investment*; funding*	1- "this will help conservation decision makers balance the opportunities for economic development with their impacts to ecosystems and make more informed decisions about development." 2- "however the window for achieving those gains is closing and without urgent and significant investment to improve management budgets and management capacity africa's pa networks will continue to deteriorate."	1 - Brown and Hamilton 2018 2 - Lindsey et al 2016
Additional Seeded (Tools and techniques)	19	Tool application	approach*; implement*; method*; apply*; techniques*	1 - "this approach identifies boundary options which provide the greatest protection of vulnerable species from their most significant stressor at limited socio-economic cost." 2- "beyond the immediate compliance optimization benefits this approach offers managers the opportunity to consider poaching risk along with other relevant elements such as additional ecosystem threats resilience potential and sociocultural and economic values which together will enhance managers' capacity to implement strategic resilience-based management."	1 - Stortini et al 2015 2- Thiebot et al 2014
Additional Seeded (Management of species, sites, or resources)	20	Monitoring	monitoring*; assess*; monitor*; survey*; surveillance*	1 - "remote sensing based monitoring systems need to be established for monitoring at large spatial scales combined with high value indicator species." 2-"we also recommend accompanying programs raising local awareness of the endemic fauna and the creation of a regular monitoring program tasked with providing the baseline data for future control and management."	1- Ambastha et al 2010 2-Herder et al 2012
Unsupervised (Management of threats)	21	Impact mitgation	measure; road; help; improve; level	1 - "by evaluating road mortality risk at multiple scales we hope to assist in developing both local and regional conservation measures for minimizing the effects of road mortality on rare turtles and similarly vulnerable taxa." 2-"in light of our data small and medium companies should be targeted for specific monitoring programs in order to clarify strategies to mitigate their apparent negative impact on wild birds' mortality in northern portugal.."	1- Beaudry et al 2008 2- García-Barcelona et al 2010
Unsupervised (Conservation planning)	22	Miscellaneous conflict, wildlife and targets	activity; wildlife; conflict; order; target; aim	1 - "overall assuming the continuation of the observed pasture conversion trend and the use of forest fire we suggest that our results should be incorporated into a spatially explicit and integrated decision support tool to target and focus land-planning activities and policies" 2-"managers can then focus control within those areas identified as conflict zones and establish surveillance schemes that prevent the loss of wildlife within the targeted areas." 3- "the comparison of these scenarios or of pre-development maps with maps of winter sport activities should enable zones of potentially high human-wildlife conflict to be recognized and sustainable wildlife-friendly management of ski resorts to be promoted."	1 – Armenteras et al 2013 2 - Márquez et al 2013 3 – Patthey et al 2008
Unsupervised	23	Research and data	understand; conservation;	1 - "Future research should focus on improving HF accuracy using more detailed higher-resolution data and seek to establish relationships between the HF and ecological processes ecosystem functions ecosystem services and human well-being to better	1 - Yin et al 2020 2- Tulloch et al 2020

(Tools and techniques)			research; data; knowledge	guide human activities." 2-"continued efforts to ensure better accuracy and completeness of entanglement and bycatch data at a national level will improve its value as a tool for monitoring cetacean interaction trends which can be used to provide important information both now and into the future on the status of threatened cetacean species."	
Unsupervised (Conservation planning)	24	Land/seascape planning	use; planning; study; landscape; propose	1 - "a composite measure of disturbance combining the effects of major landscape patterns and processes provides an important component for the design of landscape restoration plans" 2- "the outputs of our model are useful for marine conservation planning because understanding the dynamics and potential impacts of land-based threats is necessary to identify spatial alternatives that can minimize vulnerability and maximize conservation outcomes."	1 - Ambastha et al 2010 2- Alvarez-Romero 2013
Unsupervised (Conservation planning)	25	Miscellaneous conservation needs	effort; conservation; need; improve; exist	1 - "consequently the urgent need of an appropriate management of los roques was recognized given the rapid increase in tourism and other human activities inside this mpa ." 2- "Thus our research suggests that funding and staffing protected areas in times of conflict is important and may be an effective conservation strategy although potentially at high costs to those enforcing protection."	1 - Croquer et al 2016 2- Butsic et al 2015
Unsupervised (Conservation planning)	26	Develop strategies	strategy; develop; need; ecosystem; forest	1 - "consequently identifying priority sites for conservation characterized by minimal human conflict that would require minimal direct investment of effort and resources for effective protection is critical" 2- "studies of the vertical and horizontal distributions of target species and protected species may allow the development of alternative gear types to maximize exposure to tar get species and minimize risk to protected species."	1 - Escobar et al 2015 2- Eguchi et al 2017
Unsupervised (Tools and techniques)	27	Risk Assessment	risk; assessment; framework; inform; effect	1 - "halting global biodiversity decline requires conservation interventions to focus on those areas that are threatened from human impact hence anticipating where future impacts may occur is essential for preventing future declines" 2-"In this context Cumulative effects assessments represent a fundamental tool to aid the identification of priority areas for conservation and management actions by identifying zones with the highest level of cumulative impact and those of priority for conservation"	1 - Di et al 2019 2-Farella et al 2020
Unsupervised (Conservation planning)	28	Evidence-based decision making	provide; study; pressure; information; strategy	1 - "overall our study provides valuable information about the determinants of spatial distribution of leopards in human-dominated landscapes that can help inform conservation strategies in the borderlands adjacent to protected areas." 2- "the findings of the present study regarding the spatial distributional patterns of selected invasion indices provides useful information that can be used to support management strategies."	1- Abade et al 2018 2-Bezeng et al 2020
Unsupervised (Conservation planning)	29	Identify priority areas	conservation; priority; area; identify; information	1 - "This information is of great importance in identifying areas potentially threatened by human impacts and could allow special attention to be directed to the river while patrolling as well as in planning conservation actions." 2- "we identify the ankalampona region majorejy natural reserve and makira natural park as conservation and restoration priorities due to its high potential species richness and low human pressure"	1-Bisi et al 2019 2-Carrasco et al 2020
Unsupervised (Tools and techniques)	30	Cost-benefit analysis	management; cost; use; benefit; action	1 - "our approach allows managers to determine priority locations where one or more actions would be most cost effective to mitigate threats" 2- "we used our results to identify where chytridiomycosis may pose the greatest risk to endangered species allowing prioritization of species regions and actions when considering research and management options given scarce conservation funds"	1-Auerbach et al 2014 2-Murray et al 2011
Unsupervised (Conservation planning)	31	Climate change impacts	change; climate; term; impact; strategy	1- "Future management of coral reefs requires a better understanding of climate vulnerability to develop appropriate strategies that will help to both human and climate impacts on marine and coastal resources and local communities " 2-" the priorities we identify will strengthen global strategies to mitigate climate change impacts."	1 - Cowburn et al 2018 2-Foden et al 2013
Unsupervised (Conservation planning)	32	Conservation across spatial scales	scale; identify; level; region; analysis	1 - "This new metric can be interpreted as a measure of ecosystem health and may be useful in the design and implementation of conservation strategies at different spatial scales." 2-" hence initially focusing retrofitting actions within the highest risk categories within a region would be a much more efficient and effective expenditure of time and money in terms of reducing golden eagle electrocutions."	1-Anjos et al 2018 2- Bedrosian et al 2020
Unsupervised (Tools and techniques)	33	Decision-support tools	decision; make; process; tool; support	1 - "such criteria could be prioritized in decision-making processes to mitigate the impacts of dams on sensitive species." 2-"the programmes provide managers and decision-makers with an essential source of relevant reliable and timely science-based information that can be used to support the decision-making process ."	1-Atkore et al 2020 2-De Noronha et al 2013

Unsupervised (Tools and techniques)	34	Mapping and modelling tools	map; model; tool; help; provide	1-" we developed a dynamic web portal to host our results online where models and analyses are updated with new lab-confirmed detections to provide managers with a useful tool to help monitor and assess the risk of as it continues to spread" 2-"The disturbance map provides a baseline against which additional disturbances from anthropogenic activities especially the activities which add pressure on the bottom communities and habitats may be measured."	1-Fortini 2019 2-Foveau et al 2017
Unsupervised (Management of threats)	35	Impact mitigation	impact; ecosystem; management; marine; information	1-"one of the benefits of our approach is that it allows managers to prioritize locations for actions to reduce risk." 2-"Species in Category B may also be targets for susceptibility studies and monitoring attention may be crucial to prevent another major population decline."	1-Arkema et al 2014 2- Berthon et al 2018

Appendix D.4: Classification of stakeholder involvement topics and themes: Interpretation of stakeholder topics with examples of studies and sample sentences

Table D.3.2. Topics among statements of stakeholder involvement in the threat mapping literature as predicted by the 10-topic Latent Dirichlet Allocation Model. Terms are those ranked within the five highest weighted words for each topic. Example sentences were chosen from the documents where the topic was the highest weighted topic.

Theme	Topic		Terms	Examples	References
Context	Land-use planning	8	species; use; land; identify; step; develop	1- "At this workshop the preliminary zoning and the functions of the zones were presented and the level of stakeholder consensus on land use was assessed." 2-"Intense discussions during the ongoing stakeholder consultations for the Kavango Integrated Land Use Plan have shown that there are conflicting multi-scale actor's appropriations of land and thus a need for steering and constant negotiations."	1 - Loki et al 2019, 2- Ronder et al 2015
Data and inputs	Selection of areas, scenarios and thresholds	1	threshold; percentage; scenario; select; include	1- "The EBSAs were selected using quantitative data and expert judgement and have been endorsed by all the contracting parties to the Barcelona Convention." 2- "The experts also agreed that where one of the factors was not present or posed only a low risk to dugongs a rating of zero was appropriate."	1 - Coll et al 2015, 2 - Grech and Marsh 2008
Data and inputs	Selection of indicators and parameters	5	conservation; area; risk; process; assessment; feedback; number; order; create	1 - "The selection of indicators and their corresponding weighting factors have been obtained by a nominal group technique of experts that allows the capture of most of the knowledge flow among experts" 2- "After communicating with stakeholders spatial determinants such as topographic hydrology forest edge accessibility and demographic were identified."	1 - Alvarez-Berastegui 2014, 2 - Deribew 2019
Data and inputs	Model parametisation and method validation	6	threat; effort; function; group; habitat; validate; ask	1 - "A panel of 13 experts consisting of researchers directly involved in field research on Sunda clouded leopards was involved in the parameterization of the model ." , 2 - "These catagorization was then validated through experts judgement in a focus group discussion among the experts."	1 - Burivalova 2020, 2 - Chettri 2013
Data and inputs	Provision of information or knowledge	10	base; species; model; result; support; opinion; determine	1 - "The deterministic growth model is based on discussions with experts and examination of a time series of aerial photographs.", 2 - "We wish to thank _ and _ for their expert input on the distribution and status of various species."	1 - Adams and Setterfield 2-25997
Planning and process	Priority and objective setting	3	data; landscape; analyze; define; government; accord	1 - "We also drew heavily on the collective expertise and experiences of a range of stakeholders.", 2 - "We found or created spatial data sets for n 25 drivers and m 19 ecosystems from a comprehensive list of 53 potential drivers and 20 ecosystems relevant to the California Current identified by several regional experts. ... Yet expert assessment revealed that seamounts are likely vulnerable to very few human activities although vulnerability to these few stressors is high."	1 - Wessels et.al 2000, 2 - Halpern et al 2009

Plannin g and process	Research planning and procedure	2	boundary; process; design; validation; plan	1-"In order to visualize the effects of harbor expansion on the MPA four scenarios were developed by eliciting experts' judgment." 2- "In order to acquire adequate information of each location a botan ical expert and a local fisherman joined each trip. Prior to the set-up of the rules the classes were predecided based on experts' recommendations on field conditions and observations ."	1 - Parravicini et al 2012, 2 - Mozumder et al 2014
Plannin g and process	Creating and modifying threat maps	7	mapping; map; knowledge; planning; region; team; quality; work; interview	1 - "Then we restricted the surface to the distribution area corrected through expert validation." 2- "Prior to map creation we solicited input from experts and their feedback was used to update the fishing effort tables and resulting maps."	1-Gaisberger et al 2020, 2 - Stewart et al 2010
Validati on and verifica tion	Verification of results or intervention design	4	use; discussion; site; study; research; input	1 - "Compiled information was returned to country experts for final verification." 2-"In order to reduce mortality among this small dolphin community the results of this study were used as a framework to design a fishing exclusion area which was discussed with local stakeholders."	1 - Clements 2014, 2 - Di Tullio et al 2016
Validati on and verifica tion	Review and validate findings	9	base; result; literature; workshop; review	1 - "Once completed the literature reviews proposed buffers and sensitivity ratings for each species were circulated amongst species' experts for comment ." 2- "The first map version was reviewed in eight workshops with 87 experts from regional environmental agencies and national natural parks."	1 - Bright et al 2008, 2-Patino and Estupinan-Suarez 2016

Appendix D.5: Supplementary data for each included article: Retrieved outcome- and stakeholder-relevant text, number of sentences retrieved, highest weighted and all present outcome or stakeholder topics: [see additional files]

** This file is available in the thesis supplementary folder

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